Failure impact analysis of isolation valves in a water distribution network

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Abstract

Isolation valves are crucial components of water distribution systems for separating pipe segments from the network for repair or maintenance purpose. This paper looks at the impacts of isolation valves failure on the three indictors including number of valves that are needed to isolate a distribution system segment, the size of distribution system segments and the shortfall in meeting demands during failure. A network with various isolation valve configurations in terms of the density of valves is used as a case study. The results obtained from the case study show that the failure of an isolation valve has substantially varying impacts on system performance during a shutdown. The density of valves in the network determines impacts of inoperable valves on a shutdown. Generally speaking, a higher density of isolation valves leads to the less impact of valve failure. Finally, several conclusions drawn from the critical valve analysis in this study could be applied to guide the isolation valve maintenance and management.

Keywords: water distribution system, isolation valves, failure, criticality analysis

Introduction

Background

Failures of water mains caused by pipe breaks regularly occur in drinking water distribution systems. Isolation valves prevent the effects of individual events from spreading throughout the system. Instead the incidents can be isolated to small distribution system segments (Walski, 1993) which can minimize their impact. Thus, isolation valves are critical for minimizing the adverse impacts of pipe breaks and repairs. There are general guidelines for valve placement in a water distribution system such as valve spacing (GLUMB, 1992). Such guidance has been available since the early days of drinking water distribution systems. For example, Folwell (1917) wrote “These [valves] can be placed any desired distance apart but one on each line at each corner or at intervals of 500 to 750 feet apart where blocks are longer than this…” It may be better to discuss valving in terms of the number of valves at each intersection rather than spacing (Walski, 2002), though there is no globally accepted value for the “right” number of valves at an intersection.

With the exception of a few papers (Trietsch and Vreeburg, 2006; Blokker et al., 2011), the impact of the failure of valves is generally not considered. Valves can fail for a variety of reasons when they are needed to be closed. This could be due to a broken valve stem or other mechanical problem (e.g. rounded operating nut), inability to locate the valve (e.g. cover paved over), or inability to turn/reach the valves due to an obstruction (e.g. a blocked valve box). Baird (2011) reported that one estimate indicated that, in American utilities, as many as 40% of distribution system valves are inoperable if they are not tested and repaired/replaced every five years. Therefore, there is a need to analyze the impacts of valve failures for informed decision making on operational and planning problems of water distribution networks.

This paper investigates the impact of valve failures on system performance represented by several indicators of isolation success. It shows how the impacts depend on the initial density of valves. The paper is organized as follows. First, the valve-related literature is reviewed in the next sub-section. Second, the assessment process and the evaluation indicators are introduced in the method section. Moreover, a case study is performed based on the indicators developed in the previous section. Finally, conclusions are drawn.

Literature review

Valving has not received a great deal of attention in the research literature in the field of water distribution system design, compared to such topics as pipe sizing, tank sizing/siting or pump scheduling. Of course, water system operators had been employing this concept of using valves to isolate breaks ever since the development of the first systems, as illustrated in previous studies (Walski, 1994; Walski et al., 2006). Rosenthal et al. (2002), Creaco et al. (2010), Giustolisi et al.(2008), Jun et al. (2007), Kao and Li (2007), Trietsch and Vreeburg (2006) and Zhuang et al. (2013) investigated methods to analyze shutdowns with valving. However, few attempts have been made to assess how the water distribution system performance such as reliability is affected by valve failures.

Early research into reliability simulated shutdowns by removing individual pipes from a network model without regard for the location of valves. However, the concept of a distribution systems segment defined by valves, which was described by Walski (1993), can be used to study the impact of valve failures. Walski (1993) defined a segment as “the smallest portion of a water distribution system that can be isolated by closing valves”. The ‘N Valves’ configuration is a valve layout fashion where the number of valves is equal to the linked pipes at a junction, and ‘N-1 Valves’ is a fashion of valving one less than the linked pipes (Walski et al., 2006), as shown in Figure 1. Several researchers including Jun and Loganathan (2007), Giustolisi and Savic (2010), Alvisi et al. (2011) and researchers from Bentley Systems (2016) developed methods to automatically identify distribution system segments.

Valve failure impact is normally assessed based on failure performance in consideration of failure probability (Jun et al., 2007; Blokker et al., 2011). However, assigning a likelihood to valve failure, can be very difficult for many water distribution systems due to lack of knowledge and data in practice. In this paper, the focus of this study is shifted from understanding the valve failure to understanding the consequence and impact of such a failure should it occur, no matter how big or small its likelihood is.

A number of indicators can be used in relation to the valve placement problem. Deb et al. (2006) developed criteria for valve locations based on system reliability. They concluded "improvements in the distribution system reliability to minimize customer interruptions can be achieved by increasing the reliability of valves and by adding new valves in critical locations." Walski (2011) presented an approach to determine the best number of valves in a system based on economic considerations. KWR carried out a series of studies regarding the valve reliability analysis using performance indicators, e.g. Customer Minutes Lost (CML), which is defined as the average time of the year when the customer cannot receive any water (Trietsch and Mesman, 2004; Trietsch and Vreeburg, 2005; Trietsch and Vreeburg, 2006; Blokker et al., 2011). Their methodology identified critical valves based on CML. However, there are few studies to use hydraulic performance related metrics, which allow for analyzing the direct impact (i.e. in the failure area) and the indirect impact (i.e. other areas where demand/pressure shortfalls are caused by the isolation) at the same time. This paper employs system property metrics and hydraulic performance related metrics including: 1) the operability of the isolation of an incident area (i.e., the number of isolation valves); 2) the surrogate indictor of a failure impact (i.e., segment length); and 3) the impact on pressure dependent water supply based on the hydraulic simulation. These indicators are then used to identify the critical valves.

Methods

Identifying critical isolation valves

Critical isolation valve identification aims to find out which failing valve would result in the most significant impact on the network. Failed valve refers to a normally open isolation valve being inoperable when needed to separate part of the network where an accidental event occurs (e.g. pipe breaks). When a valve fails, in order to be still able to isolate the incident area, the nearest downstream or upstream isolation valves are operated instead to substitute the failed isolation valve. The procedure to identify critical isolation valves is described here:

Step 1. A valve failure scenario is set up via an assumption that a specific isolation valve is failing in the network. The failing isolation valve cannot be closed when required. Failing isolation valves are analyzed one by one in each failure scenario in this study. A base case scenario with all isolation valves in operation is also considered to compare with the failing isolation valve scenarios(Creaco et al., 2012).

Step 2. Several indicators (described below) are calculated for each isolation segment, first assuming all valves are operable.

Step 3. Then each valve is failing. This results in the two segments that were connected by the valve being merged into a single new, larger segment. The indicators are then calculated. A comparison is made between the indicators with and without the valve in service.

Evaluation indicators

Due to isolation valves closure, a set of independent segments, not connected to any source, is set up. The effect of isolation valves on the system performance is reflected by the impacted segments (Mugume et al., 2015). The importance of any valve is determined not by the value of an indicator but by the change in the value when the valve shifts from operable to inoperable. The indicators are adopted in this study including

1. Number of isolation elements needed to successfully isolate a segment,
2. Segment length and
3. System supply shortfall (i.e. demand not satisfied), both instantaneously and over an extended time.

The first two indicators are the property related metrics representing the characteristics of the segments that are assessed, and the third is an indicator of hydraulic performance. The definitions of the indicators are as follows,

Number of isolation elements is the number of valves that are used to isolate a segment. In the model, isolation elements could include a variety of valves, such as isolation valve, pressure reducing valve, flow control valve, etc. Note that the flow/pressure control devices cannot function as the isolation devices in reality, but they are usually accompanied by isolation valves (e.g. gate valves and butterfly valves) for maintenance/repair use. In the model, the isolation valves around the control devices are not explicitly included, so the control devices could be allowed to serve as the boundary of the segment. The indicator of number of isolation elements can represent the complexity of closing valves when isolating an incident area. The more valves are needed to close, the more time one spends on locating and operating and the greater the likelihood that one or more of the valves will be inoperable. Ideally only two valves should be required but four is usually considered an acceptable number.

Segment length represents the total length of pipes in a segment. The segment length indicator can be related to the number of customers out of service, assuming customers are relatively evenly distributed, and also gives an indication of likelihood that any segment will need to be shut down due to a pipe break. The larger the segment length (assuming a uniform break rate per km per year) is, the greater the likelihood it will need to be shut down.

System demand shortfall is the difference between total demand and total water actually supplied for all demand nodes during a segment shutdown. System demand shortfall results give an indication of the system hydraulic performance in terms of the amount of demand met when the shutdown of a segment occurs.

System demand shortfall includes: 1) demands at nodes that are not connected to the source plus 2) the amount of water not supplied due to inadequate pressure. Pressure dependent demand (PDD) analysis has an ability of quantifying the system performance when an abnormal event occurs. Therefore, the PDD method applied to the critical valve identification/regulation and pipe design is recommended by many researchers (Tucciarelli et al., 1999; Wu and Walski, 2006; Giustolisi et al., 2008; Creaco et al., 2010). With PDD, a continuous relationship between demand met and pressure is used, and the supply becomes a constant below the minimum pressure or above the pressure threshold. Supply is deemed to be independent of nodal pressure when above the threshold (Giustolisi et al., 2008). The relationship between supply and pressure used in this study is a power function, and some alternative formulations can be found in Wagner et al. (1988), Fujiwara and Ganesharajah (1993) and Tucciarelli et al. (1999). The mathematical expression used here (Wu et al., 2009; BentleySystems, 2016) is given in Equation 1.

$$Q_i^s = \begin{cases} 0 & H_i \le 0 \\ \left(\dfrac{H_i}{H_{ri}}\right)^{\alpha} Q_{ri} & 0 < H_i < H_t \\ \left(\dfrac{H_t}{H_{ri}}\right)^{\alpha} Q_{ri} & H_i \ge H_t \end{cases} \qquad (1)$$

where H_i is the calculated pressure at node i; Q_{ri} is the requested demand or reference demand at node i; Q_i^s is the calculated demand (actual supply) at node i; H_{ri} is the reference pressure that is deemed to supply full requested/reference demand; H_t is the pressure threshold above which the supply is independent of nodal pressure; α is the exponent of pressure demand relationship. For this formulation of the relationship between pressure and demand, Equation 1 provides more flexible uses for a PDD analysis than that in Wagner et al. (1988). For example, leakage and fire flow could continuously increase when the actual pressure exceeds the reference pressure (H_{ri}). Also, the reference pressure and the pressure threshold (H_t) could be set equally, i.e. $H_{ri} = H_t$, which is consistent with the formulation in Wagner et al. (1988).

Steady state and extended period simulations (EPS) are used to calculate the system demand shortfall. Steady state runs are useful for identifying the results of outages which are not particularly long (e.g. less than an hour). With extended period simulation runs, the effects of the shutdown on tanks draining (or filling) are determined. EPS runs are much more likely to have nodes that become disconnected such that the hydraulic calculations will not balance. The analyses based on connectivity only and steady state runs are snapshots which give shortfall in flow units (e.g. liter per second), while the EPS runs calculate shortfall in volume units (e.g. cubic meter).

In this study, segmentation and PDD methods are implemented using Bentley WaterGEMS software (Jun and Loganathan, 2007; Wu et al., 2009). The alternative software tools include KWR OptiValves, Innovyze InfoWorks, etc. The Criticality module calculates the basic indicators' values for all segments. In some cases, the systems become so disconnected because of valve closures that the hydraulic equations cannot be solved and independent manual calculations are implemented for calculating shortfall.

Case study

The case study network consists of 279 pipes and 188 junctions, where the total pipe length is 21 km and the diameter ranging from 101 mm to 203 mm. There are two pumps feeding water to the network from the lower elevation reservoir at the northeast side of the system and a tank located at the southwest side, as shown in Figure 2. The pump controls are determined by tank water level. In the model the demands are loaded at mid-pipe rather than at cross junctions because the customers are located along a pipe, not at junctions and that difference is important in the valve segmentation calculations. The demand pattern shown in Figure 3 is consistent for all demand nodes in extended period simulation runs.

In this network layout, only isolation valves are used as isolation elements, and four configurations of isolation valves are set up according to gradually decreased density of isolation valves, as shown in Table 1. Other than N Valves and N-1 Valves fashions introduced previously, Limited Valves and Scarce Valves fashions subsequently reduce valves on the basis of the N-1 Valves. For the valve configurations, the valve elimination is based on the prior, more valves configuration. For example, N-1 Valves is transformed into Limited Valves by the reduction of a few valves. The missing valves usually tend to be the valve placed on the upstream pipe (i.e. the pipe where water most commonly flows to the node).

In Equation 1, the exponent of the function is set to 0.5. The pressure threshold is set to 20 m, above which the demand is fully met. H_{ri} is set to the same value with the pressure threshold (H_t).

Results

This section shows the impact of a single valve failure on the three indicators described above.

Number of isolation elements

Figure 4 shows the results of the number of isolation elements with and without a valve failure. The black columns represent the number of isolation elements when the isolation valves are in operation, while grey column heights are the total number of isolation elements when one isolation valve is out of service. For the N Valves configuration, most pipe segments can be isolated by two valves in the all isolation valves operating case. When one of the isolation valves is failing, the number of isolation elements will increase to three for “T” shape intersections or four for the cross junctions (see Figure 4a). For the N-1 Valves configuration, the greatest increase in the number of isolation elements is 2, while the increase is 5 for the

Scarce Valves configuration. The isolation elements indicator changes fairly largely for different valve configurations and the greatest value of the indicator corresponds to different failed valve scenarios, which indicates that the critical isolation valve identified by the isolation elements indictor is highly related to valve layout and network topology.

In Figure 4, the number of isolation elements increases (grey column height minus black column height) with the decrease in density of valves. The density of valves initially impacts the number of valves that need to be operated when all are operating, but the more significant problem is that as the density of valves decreases and a valve fails, the number of extra valves that must be operated increases. In this sense, having an inoperable isolation valve is equivalent to making the isolation valve configuration sparser. The network with reduced valves requires operation of more valves to isolate an incident area, which implies longer valve operating time and more valve failure risk.

The total height of the column in Figure 4 corresponds to the number of isolation valves needed for isolation when the targeted isolation valve fails. The maximum height in Figure 4d is 10. Investigation of the location of this 10-valve segment shows that it lies at the right of the network, linking the nearest segment to the tank, of which the other end extends into the meshed network (Seg-1 in Figure 5). This result is primarily contributed to 7 isolation valves by the meshed network that has lots of alternative paths. Therefore, it is inferred that the need for more isolation valves tends to occur in highly meshed networks with a scarce valve configuration.

The indicators statistics are calculated to investigate the changes of isolation elements for a specific valve configuration and also to compare various isolation valve configurations. A summary of average numbers of isolation elements is shown in Table 2. If one of the valves fails, the isolation element count will increase in comparison with the count in operable scenarios. It is worth noting that on average more than one valve is needed to compensate for a single failed valve. The sparser the density of valves is, the more compensation valves are needed. The extra compensation valves reaches up to 104% for the Scarce Valves configuration.

Segment length

Figure 6 shows the results of the segment length indicator in the isolation valve operable (black column) and inoperable (grey column) states. The smaller segment length is chosen as a representative between the two segments that the target valve links when the valve is in the operable state, since a larger difference of this indicator could be shown before and after the valve failure. The segment length, when the valve is inoperable, is combined by the two segments that are linked by the failing valve. For most valve failure scenarios, segment length has an obvious change in all valve configurations. The greatest increase is derived from the valve failure at the round circle network (Seg-2 in Figure 5). In some way we cannot emphasize that the valves in that area are really critical, because it is located near the boundary of the network and does not impact any downstream segments, and the outskirt area usually has sparser users distributed along the pipes.

As can be seen in Figure 6a, the N Valves configuration has very small segment lengths when all valves are operating, and these segments usually appear at junctions, that is a cross junction is surrounded by four isolation valves in each incident pipe. If there are four valves at a cross, there are usually no customers connected in that segment. The segment around the junction implies the lower failure ratio due to the shorter pipe length. In addition, from the point of view of the uniformity of segment length for linking segments, N-1 Valves and Limited Valves configurations show a good tradeoff that they don’t have valve redundancy, such as the N Valves configuration ubiquitously has very small segments (the black columns in Figure 6a), nor as significant impact as the Scarce Valves configuration (the grey columns in Figure 6d).

Table 3 shows the statistical results of average segment length before and after an isolation valve fails. The segment length, in valve operable and inoperable states and the changes between them, increases with the decrease in the density of valves. The segment lengths exhibit considerable increases for all configurations (the relative changes of segment length are shown in the brackets in Table 3). In particular, in the N valves configuration, the segment length increases by about 4 times for a majority of failing valves.

System supply shortfall

Figure 7 shows the system supply shortfalls when the isolation valves are operating or failing. For all valve configurations, the supply shortfalls exhibit significant increase before and after one of the isolation valves fails. In the N valve configuration (Figure 7a), a number of supply shortfalls in the failure scenarios (i.e. black columns) are equal to zero, which indicates the isolated segments do not include any demands, nor induce the pressure drop below the prescribed pressure threshold (i.e. below 20 m) due to network shutdown.

In Figure 7d, there is a valve failure scenario which shows a far greater shortfall value than other failure scenarios. This isolation valve (i.e. Valve 79) is laid on the mains which links the tank and the reservoir, and in the Scarce Valves scenario this valve becomes the only existing isolation valve for a long distance in that route. This segment of mains links two inlets of a large area of the network (that linking to Seg-4 in Figure 5, roughly one third of the network). If the isolation valve is failing, isolation of the new segment of mains puts all of the water users in the right bottom portion of network out of service. This isolation valve is critical in this case. In contrast, this valve also exists in the other three valve configurations but its failure does not have as large of an effect, and thus it implies that the criticality of an isolation valve is highly dependent on the valve layout.

The isolation valves with the great values of shortfall (Valve 43, 44, and 167 in Figure 7a, Valve 37 and 38 in Figure 7b, Valve 31 and 32 in Figure 7c) are consistently associated with a segment which includes a single link that connects an independent network to the mains (the network linking to Seg-3 in Figure 5). These valves will result in a complete outage for a large portion of the network when one of them is failing. Therefore, it implies that the valves in the segment containing the inlet of a large, branched network are critical.

The shortfall values before and after one of the valves fails are shown in Table 4. Similarly, the results of shortfall in supply increase with the decrease in the density of valves. The changes of shortfall take on several times larger than the shortfall when all of the valves are operable. It demonstrates that segment shutdown when one valve fails could result in a much more significant impact than that of the operating valves (3~4 times larger in this case). The percentages in Tables 4 represent the percent of system demand that is not met.

Extended period simulation analysis

The segment isolated for a long period can be simulated in EPS. It is assumed that the period of restoration or maintenance lasts for 24 hours in this study. Figure 8 demonstrates the results of the system supply shortfall indicator in EPS runs. In general, only a few valves can lead to a large shortfall. These valves which cause serious shortfalls appear to aggregate in approximately the same ranges for all configurations. Therefore, the shortfall values in this case are divided into 4 “ranges” with thresholds of 1,200 m^3, 600 m^3, and 200 m^3 (i.e. dashed line shown in Figure 8), which correspond to 72%, 36%, 12% of total supply, respectively. There are three valves leading to excess of 1200 m^3 in all four valve configurations. The shortfall values in the second range all concentrate between 600 m^3 and 800 m^3 except the Scarce Valves configuration. The shortfalls in the third range also have approximately similar values. Overall, we find strong correlations among the four valve configurations.

The locations of the isolation valves in the three most important zones are plotted in Figure 9a, of which the system supply shortfalls are larger than 200 m^3 (see in Figure 8). The isolation valves (Valve-41, Valve-164, Valve-72) in Zone 1 in Figure 9a surround the pump station, and the detailed structure of Zone 1 is shown in Figure 9b. The valves in Zone 2 in Figure 9a are located in close proximity to the segment that is the only way linking between the pump station and tank, termed as key segment (shown in Figure 9c). Water users to the east of that segment can be supplied if the segment is shut down, but to the west, users will only be supplied until the tank drains. The supplied amount is equal to the initial volume of the tank. The third zone valves in Figure 9a are concentrated around a key segment that links the water source and a branched network with a single supply. The shortfall corresponds to the demand in the areas. In general, valves whose failure prevents the main pump station from supplying water are the most critical. When the main pump station cannot supply water, the remainder of the system must be fed from the tank which has a finite capacity which is exhausted in a 24 hour period. A larger tank or a faster repair would reduce that impact.

As the configuration of valves becomes sparse, the segments are enlarged. Thus more isolation valves become critical in order to isolate the important segments from the location needing to be shut down, according to Figures 8 and 9.

The critical isolation valves are usually associated with key segments. The isolation valves (Valve-153 and Valve-157 in Figure 9c) that are placed on the key segments correspond to the black columns in Figure 8a. It indicates there is a significant impact on the demand shortfall once this valve is closed. Moreover, another type of isolation valve that can induce the enormously incremental shortfall if it fails is located in the proximity of the key segment (e.g. Valve-35, Valve-36, Valve-37, and Valve-152 in Figure 9c).

Table 5 summarizes the supply shortfall in EPS runs. In general, there is an ascending trend of the impact on shortfalls with the decrease in the number of valves. The less the number of valves, the greater the degree of shortfall (i.e., the greater the percent of shortfall change). The Limited Valves configuration has a lower shortfall value than the N-1 Valves configuration in the valve operable state, due to some extreme values (see Figure 8) derived from the special position of valves. The volumes of shortfall in EPS are converted into mean flow rates in the 24 hours horizon, allowing for a comparison with the results in the steady state. For the valve operable state, the EPS produces the moderate increase in the shortfall in comparison to that of the steady state simulation (Table 4), but for the valve inoperable state, the EPS exhibits a more significant impact on supply shortfall. That is because the tank that is drained within the

EPS enhances the influence of valve closure and also exacerbates the impact of valve failure.

Discussion

While increasing the number of valves leads to a more reliable system, not all valves are of equal importance. Failure of a valve adjacent to a pump station, tank, major transmission pipe or the beginning of a branched (i.e. tree shaped) portion of the system can have much greater impact than failure of a pipe in a highly looped portion of the system away from major facilities. While valves on hydrant laterals are not included in this study, it is easy to see that those valves are especially important when they are located on major transmission pipes such that failure of a small valve can impact a major component of the system.

Identification of valves whose failure can have serious consequences can help water utilities prioritize valve maintenance work. Identification of key valves not only indicates where additional valves may be required during design but also where maintenance activity should be focused.

The three indicators used for a valve criticality analysis are introduced in this paper. The indicator of system supply shortfall is principally recommended because this indicator can directly reflect the impact of how much water cannot be supplied in the isolated area. Moreover, this indicator also takes into account the impact of the supply shortfall due to inducing more head loss. However, the indicators of segment length and number of isolation valves are two good surrogate measures when a well calibrated hydraulic model is not available or the massive hydraulic simulations are infeasible in large water network systems, e.g., in the valve reliability assessment and valve optimization placement. Also, the segment length indicator takes the advantage of data accessibility over the indicators associated with impacted customer survey. The latter two approximately evaluate the impact of the failed valves on the system performance but are more straightforward and easy to use. The schedule of valve maintenance work could be also based on the priority with respect to different indicator results in the criticality analysis.

Conclusions

This paper presents a failure impact analysis method that can identify the most critical valves using a set of indicators in water distribution systems. In the method, one isolation valve in a network is assumed to fail in a failure scenario. Based on the valve failure scenarios, the performance of segments (or overall network) is examined by a set of three indicators which are the number of isolation valves needed for shutdown, segment length and system supply shortfall (for both an instantaneous and extended period). Using these indictors, it is possible to determine which isolation valves are most critical throughout the network. The case study is applied in a realistic water distribution network with four different valve configurations in terms of the density of valves. We can draw the following general conclusions in this study:

1) As more isolation valves are included in a system, the impact of the failure of any one valve becomes less severe. Specially, the three indicators consistently increase (i.e. performance becomes worse) with the decrease in the valve density.

2) Critical valves are often associated with key segments, i.e. the ones containing sources or linking a large portion of the network with a single inlet. In multiple source systems, tanks play a key role of minimizing the impact of segment outage at least for a short time period of outage.

3) The critical valves are strongly associated with network topology and valve layout. Isolation valve number is inherently crucial for water network management, and the proper placement of valves is able to mitigate the impact of incidents to a great extent.

4) The failure of some valves only affects a small area while the failure of others can have system-wide implications.

The number of valves is closely related to cost, both of valve construction and valve maintenance. Minimizing the number of valves, however, has a substantial effect on the indicators. There exists a tradeoff between cost and benefit of valve placement (Creaco et al., 2010). The future work is suggested to investigate how the impact of valve failure, and also the combination of multiple valve failures, is related to the cost of valve placement.

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Table 1. The number of isolation valves and segments in various valve configurations

Configuration	Number of isolation valves	Number of segments
N Valves	183	157
N-1 Valves	130	104
Limited Valves	112	86
Scarce Valves	91	65

Table 2. Average number of isolation elements

Valve configuration	Average number of isolation elements when valves are operable	Average number of isolation elements when one valve is out of service	Incremental number of isolation elements
N valves	2.0	3.1	1.1 (55%)[a]
N-1 valves	2.3	3.8	1.5 (65%) [a]
Limited valves	2.5	4.4	1.9 (76%) [a]
Scarce valves	2.7	5.5	2.8 (104%) [a]

[a] Relative change of incremental number of isolation elements = the incremental number of isolation elements / the average number of isolation elements when valves are operable

Table 3. Average segment lengths

Valve configuration	Average segment length when valves are operable (m)	Segment length when one valve is out of service (m)	Segment length change (m)
N valves	12.6	61.1	48.5 (385%)[a]
N-1 valves	33.3	105.0	71.7 (215%)[a]
Limited valves	39.4	129.1	89.7 (228%)[a]
Scarce valves	60.3	188.0	127.7 (218%)[a]

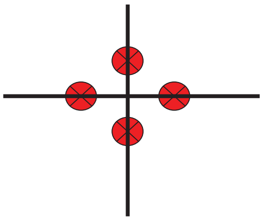
[a] Relative change of segment length = change length / segment length in the valve operating state

Table 4. Average system supply shortfalls in steady state

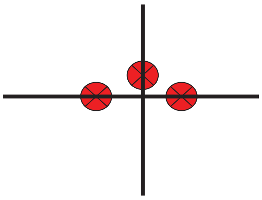
Valve configuration	Shortfall when valves are operable		Shortfall when one valve is out of service		Shortfall change	
	(L/s)	(%)	(L/s)	(%)	(L/s)	(%)
N valves	0.09	0.5	0.35	1.8	0.26	1.3
N-1 valves	0.17	0.9	0.58	3.0	0.41	2.1
Limited valves	0.21	1.1	0.72	3.7	0.51	2.6
Scarce valves	0.32	1.7	0.99	5.1	0.67	3.4

Table 5. Average system supply shortfalls in EPS

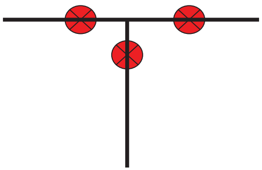
	Shortfall when valves are operable			Shortfall when one valve is out of service			Shortfall change		
	(m^3)	(L/s)	(%)	(m^3)	(L/s)	(%)	(m^3)	(L/s)	(%)
N valves	16	0.19	1.0	73	0.84	4.4	57	0.65	3.4
N-1 valves	21	0.24	1.3	105	1.22	6.3	84	0.98	5.0
Limited valves	20	0.23	1.2	119	1.38	7.2	99	1.15	6.0
Scarce valves	38	0.44	2.3	182	2.11	10.9	144	1.67	8.6



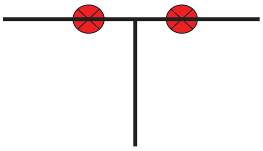
N valves at cross



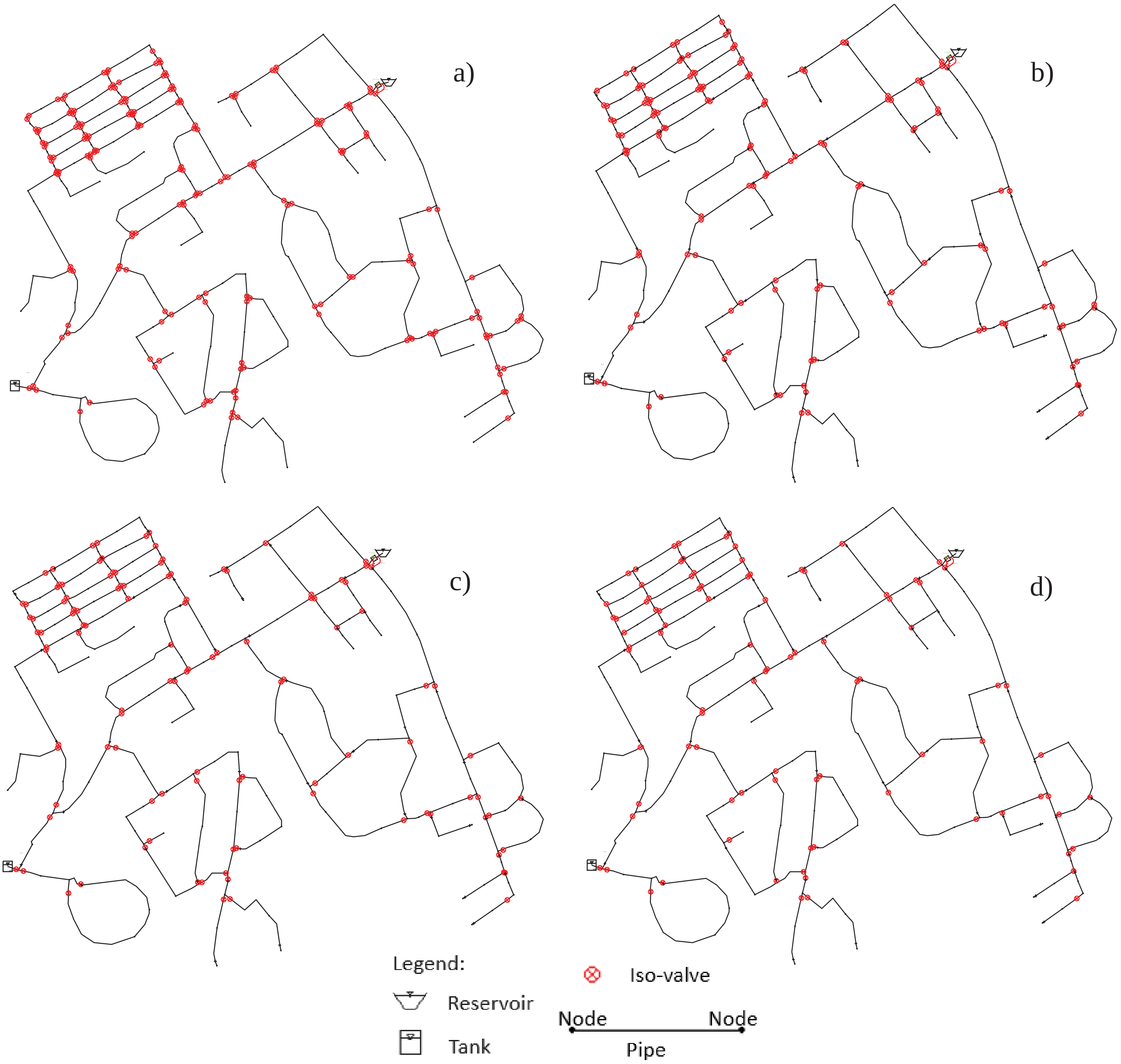
N-1 valves at cross

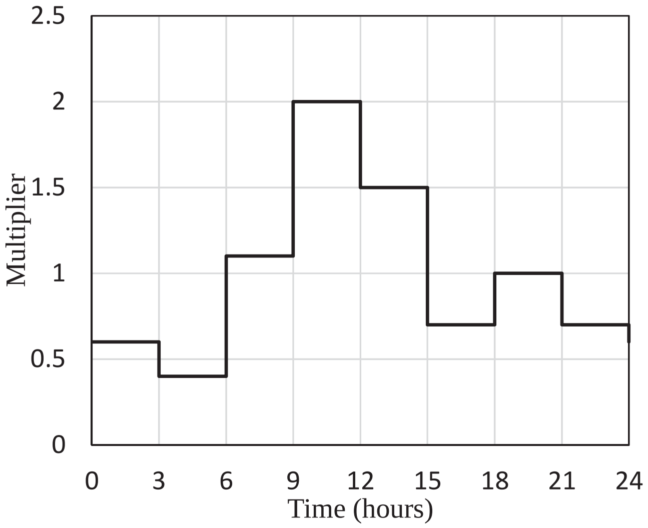


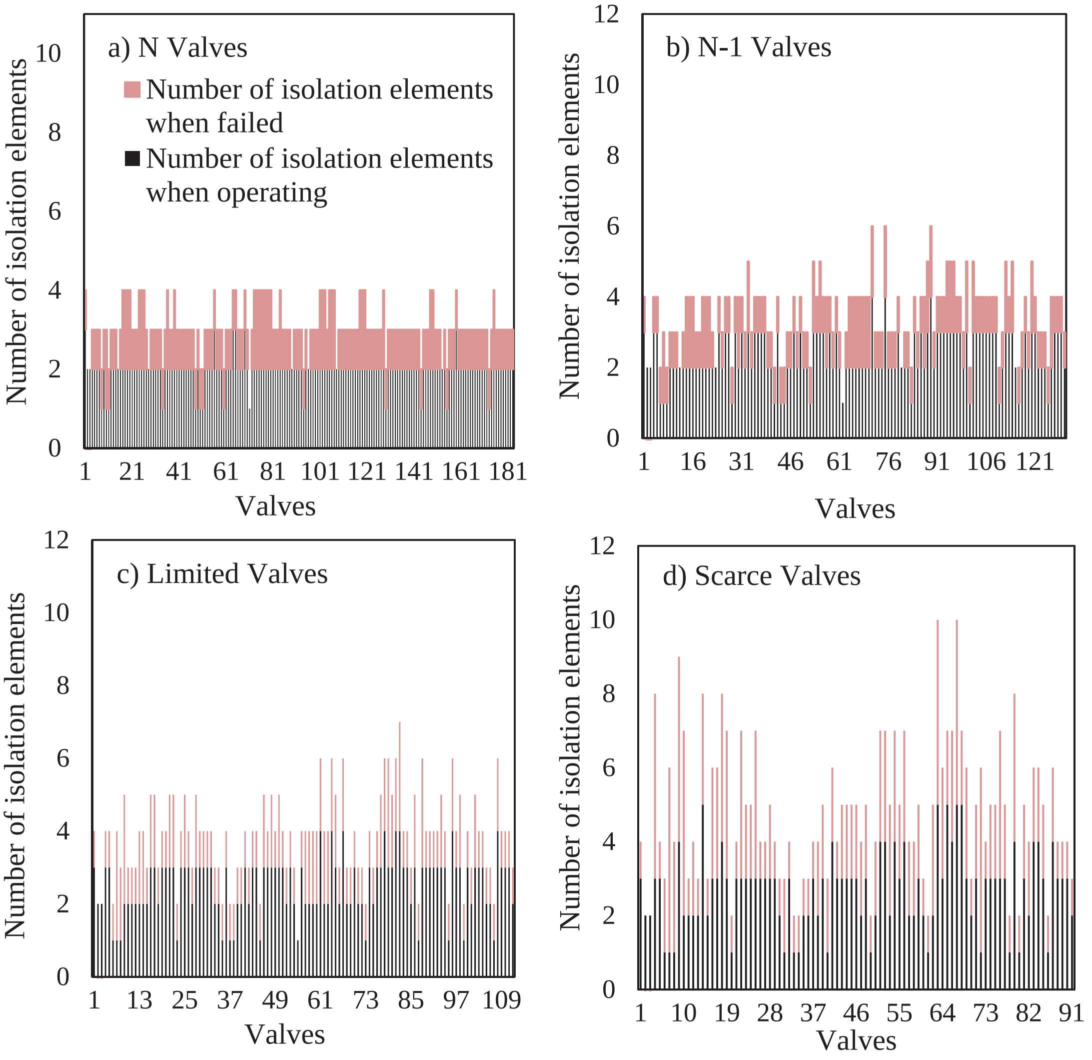
N valves at T



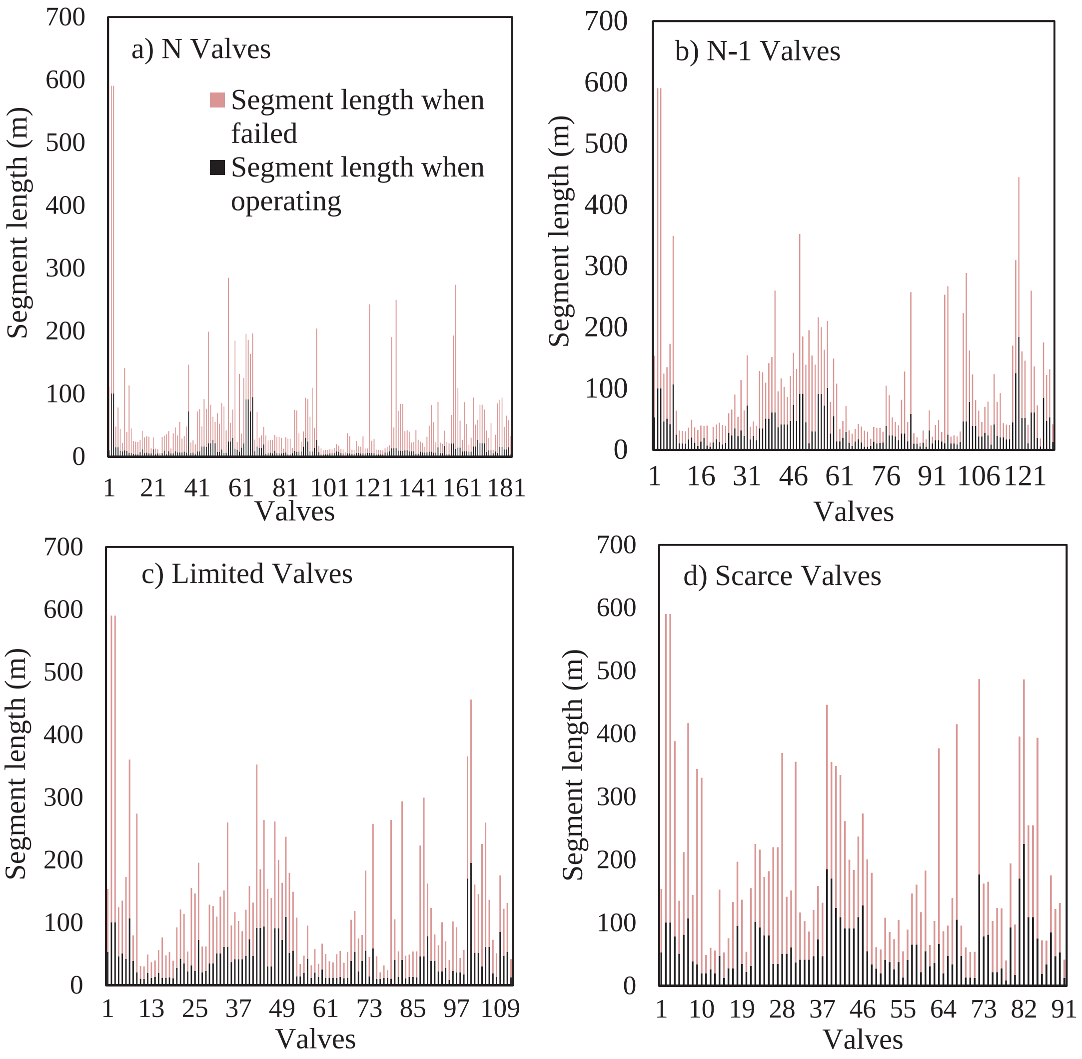
N-1 valves at T

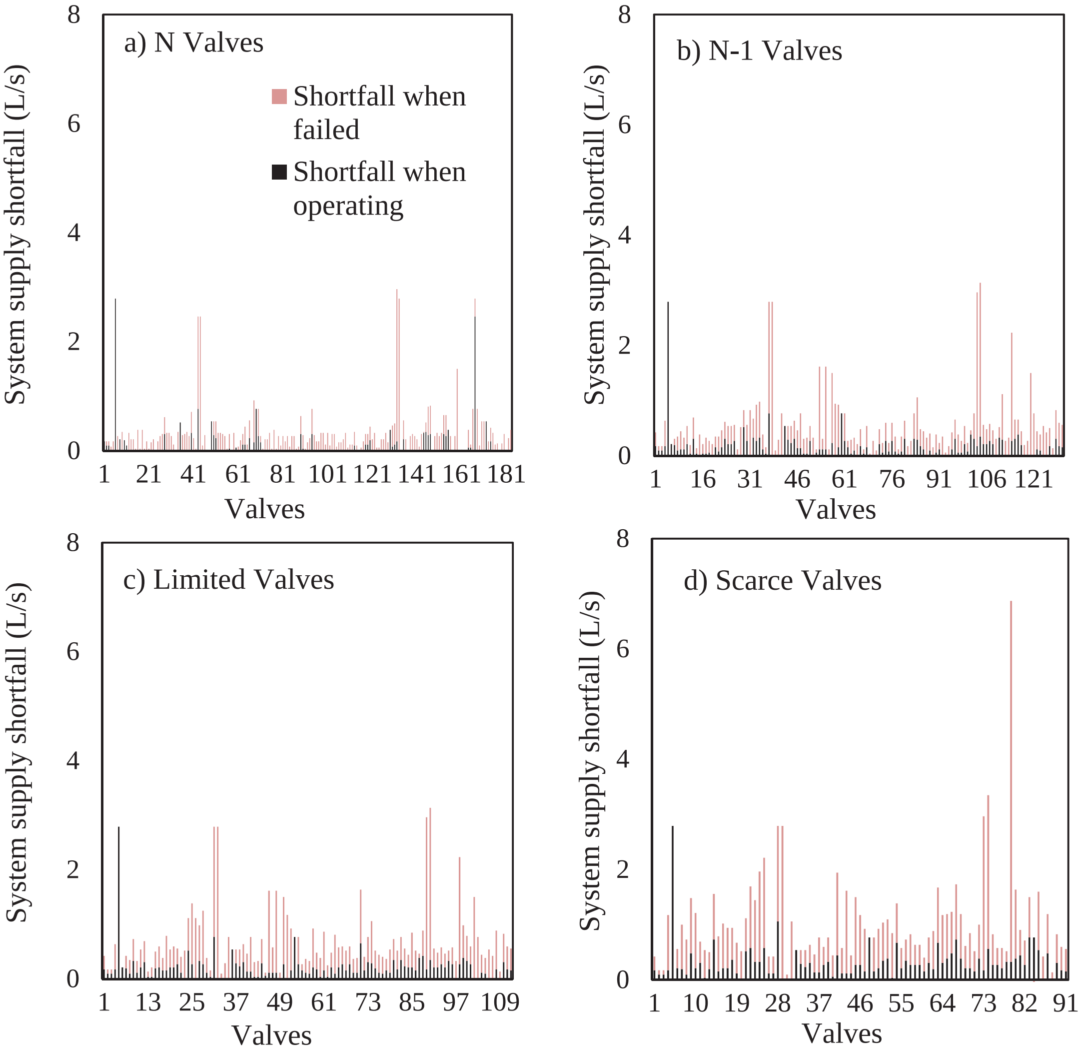

a)
b)
c)
d)
Legend:
Iso-valve
Reservoir
Tank
Node
Node
Pipe

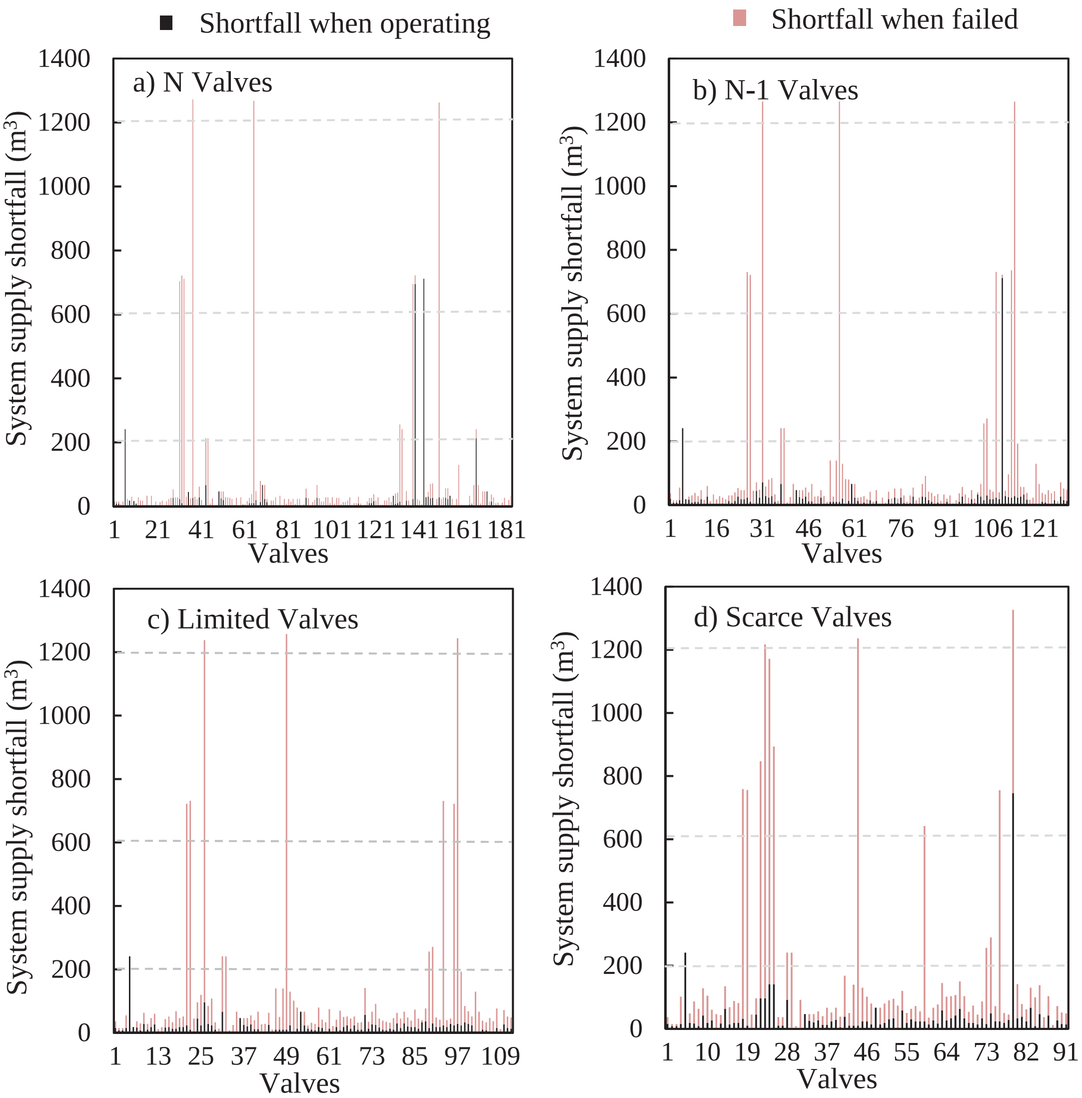

2.5
2
1.5
1
0.5
0
Multiplier
0
3
6
9
12
15
18
21
24
Time (hours)


a) N Valves
Number of isolation elements when failed
Number of isolation elements when operating
Number of isolation elements
0
2
4
6
8
10
1
21
41
61
81
101
121
141
161
181
Valves
b) N-1 Valves
Number of isolation elements
0
2
4
6
8
10
12
1
16
31
46
61
76
91
106
121
Valves
c) Limited Valves
Number of isolation elements
0
2
4
6
8
10
12
1
13
25
37
49
61
73
85
97
109
Valves
d) Scarce Valves
Number of isolation elements
0
2
4
6
8
10
12
1
10
19
28
37
46
55
64
73
82
91
Valves


Failing valve
Seg-4
Failing valve
Seg-1
Seg-3
Failing valve
Failing valve
Seg-2


a) N Valves
■ Segment length when failed
■ Segment length when operating
Segment length (m)
0
100
200
300
400
500
600
700
1 21 41 61 81 101 121 141 161 181
Valves
b) N-1 Valves
Segment length (m)
1 16 31 46 61 76 91 106 121
Valves
c) Limited Valves
Segment length (m)
1 13 25 37 49 61 73 85 97 109
Valves
d) Scarce Valves
Segment length (m)
1 10 19 28 37 46 55 64 73 82 91
Valves


a) N Valves
Shortfall when failed
Shortfall when operating
b) N-1 Valves
c) Limited Valves
d) Scarce Valves
System supply shortfall (L/s)
0
2
4
6
8
Valves
1 21 41 61 81 101 121 141 161 181
1 16 31 46 61 76 91 106 121
1 13 25 37 49 61 73 85 97 109
1 10 19 28 37 46 55 64 73 82 91


■ Shortfall when operating
■ Shortfall when failed
a) N Valves
b) N-1 Valves
c) Limited Valves
d) Scarce Valves
System supply shortfall (m^3)
Valves
0
200
400
600
800
1000
1200
1400
1 21 41 61 81 101 121 141 161 181
1 16 31 46 61 76 91 106 121
1 13 25 37 49 61 73 85 97 109
1 10 19 28 37 46 55 64 73 82 91

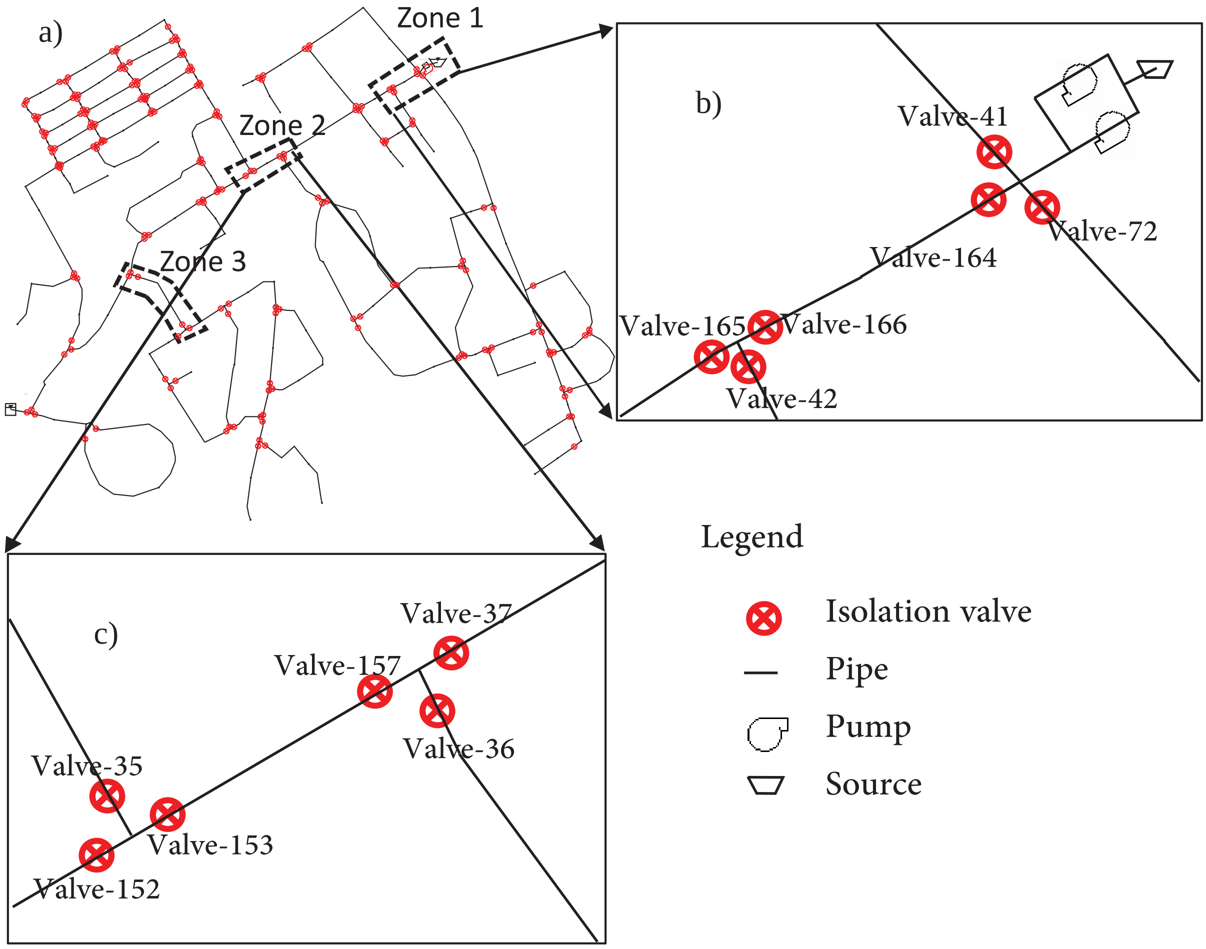

a)
Zone 1
Zone 2
Zone 3
b)
Valve-41
Valve-72
Valve-164
Valve-165
Valve-166
Valve-42
c)
Valve-37
Valve-157
Valve-36
Valve-35
Valve-153
Valve-152
Legend
Isolation valve
Pipe
Pump
Source

Figure Caption List

Figure 1. Valving approaches

Figure 2. The schematic of the case network and the four valve configurations considered: a) N Valves; b) N-1 Valves; c) Limited Valves; and d) Scarce Valves.

Figure 3. Hourly demand pattern for the case network

Figure 4. Number of isolation elements before and after one valve failed

Figure 5. The most significantly impacted segments. Seg-1 is the segment that includes the most isolation valves; Seg-2 is the longest segment (scaled in the model); Seg-4 and Seg-3 correspond to the segments with first largest shortfall and second largest shortfall in the steady state simulation, respectively.

Figure 6. Segment length variation before and after one valve failed

Figure 7. System supply shortfalls before and after one valve failed in steady state

Figure 8. System supply shortfalls before and after one valve failed in EPS

Figure 9. Location of critical isolation valves in extended period simulation