Management of water distribution systems in PDA conditions using isolation valves: case studies of real networks

A. Fiorini Morosini, O. Caruso and P. Veltri

ABSTRACT

The current paper reports on a case study investigating water distribution system management in emergency conditions when it is necessary to seal off a zone with isolation valves to allow repair. In these conditions, the pressure-driven analysis (PDA) is considered to be the most efficient approach for the analysis of a water distribution network (WDN), as it takes into account whether the head in a node is adequate to ensure service. The topics of this paper are innovative because, until now, previous approaches were based on the analysis of the network behaviour in normal conditions. In emergency conditions, it is possible to measure the reliable functioning of the system by defining an objective function (OF) that helps to choose the optimal number of additional valves in order to obtain adequate system control. The OF takes into account the new network topology by excluding the zone where the broken pipe is located. The results show that the solution did not improve significantly when the number of valves reached a threshold. The procedure applied to other real case studies seems to confirm the efficiency of the methodology even if further examination of other cases in different conditions is necessary.

Key words | hydraulic reliability, isolation valve system, water distribution network (WDN)

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INTRODUCTION

In a real network, valves along pipes allow a zone to be isolated when it is necessary to operate on the system. Correct management suggests limiting the number of valves in a network due to their cost as well as to operating problems; however, an increased number of valves and their correct use guarantee good system performance in both normal and emergency conditions.

The network area where a broken pipe is located can be isolated by using a set of shut-off valves. Since the goal of isolating a broken pipe can be achieved with different subsets of operating valves, it is essential to define their position and analyse the system in the related different topologies.

Many authors have addressed water distribution network (WDN) management problems, in order to gain a better understanding regarding the choice and planning of the location of isolation valves. The first studies considered the problem of pipe rehabilitation and their goal was to prevent pipe bursts using network management (Engelhardt *et al.* 2000; Dandy & Engelhardt 2001); therefore, valve positioning was considered as a secondary aspect. Gupta *et al.* (2014) propose an iterative procedure to increase network reliability avoiding problems caused by pipe failure. The proposed

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methodologies are based on the redundant use of pipes and valves.

The approaches for choosing both the position and the number of the valves for the occurrence of either planned or unplanned interruptions differ. Some authors (Creaco *et al.* 2010; Giustolisi & Savic 2010) have proposed an algorithm based on a topological matrix. Instead, Alvisi *et al.* (2011) suggest a method to identify where isolation valves for network segmentation should be located based on a pseudo-inverse matrix. Giustolisi & Ridolfi (2014) present a multi-objective strategy for optimal network segmentation using a modularity index to identify groups of nodes with strong interconnections. Perelman & Ostfeld (2011) propose a new methodology for the partition of WDN based on a clustering algorithm and on topological and hydraulic connectivity properties, whereas Gao (2014) proposes an approach based on graph theory applying it in the analysis of high dimension networks.

Other authors (Giustolisi *et al.* 2014) have adopted an optimization procedure to define the valve subsets in the network according to the hydraulic parameter changes corresponding with inadequate network conditions. The new approach was obtained by minimizing costs and by fixing constraints on nodal heads.

Some authors (Korkana *et al.* 2016a, 2016b) adopted techniques based on genetic algorithms to obtain district metered areas (DMAs) and solve the problem of water loss management.

Other approaches separate a WDN into districts providing an optimal placement of isolation valves to achieve a water pressure management to reduce water losses and to improve water quality preventing disinfection by product growth (Gonelas *et al.* 2017).

Recently, other authors have proposed methodologies to ensure that the delivered water is of an appropriate age and pressure (Chatzivasili *et al.* 2018, 2019). These approaches are based on the concept of dividing the WDN into smaller areas via the geometric partitioning method; subsequently, the Student's *t*-mixture model or Gaussian mixture modelling is applied to each area defining the position of the valves and separating DMAs.

The approach described (Fiorini Morosini *et al.* 2018) is based on the network analysis by calculating the value of an OF in order to obtain the optimal number and better location of isolation valves in some real cases. The improvement index for system behaviour is the decreasing of OF (Fiorini Morosini *et al.* 2017). Starting from an initial condition, characterized by a set of existing valves, it is possible to determine the minimum number of additional isolation valves to limit disruptions in the network when a failure occurs in one or more pipes. The proposed methodology is based on a pressure-driven analysis (PDA) model and requires the definition of the head value $H_{\max}$ to satisfy the requested demand at each network node. The approach does not provide an indication to prevent the burst; however, it does allow for operation in emergency conditions.

METHODOLOGY

A failure in a WDN modifies the amount of circulating flow and, in any case, the functioning conditions differ from those in normal conditions.

A failure in a pipe requires isolation, not only of that pipe, but also the entire zone where the pipe is located which is delimited by a subset of shut-off valves. When the valves are active, the topology of the system changes and it can determine its inefficiency. The analysis of the new system is necessary, and the new results must be analysed. If the head in a specific node is inadequate, it is impossible to deliver the requested nodal demand necessary to satisfy users' needs.

The head value $H_{\max}$ at each node is related to the ground level (z) and to the height of each supplied building (H_b); it is defined by the relationship:

$$H_{\max} = z + \frac{p}{\gamma_{\min}} = z + H_b + P_{ms} + P_p + P_D \quad (1)$$

where:

- $p/\gamma_{\min}$ is the minimum pressure head necessary to serve the users; it is related to building height H_b and to the parameters listed below;
- P_{ms} is the minimum pressure to allow the use of all devices in the building, usually 5 m;
- P_p are the head losses along the riser column;
- P_D are the head losses starting from the network node and ending at the base of each building.

When the head is lower than $H_{\max}$, the system works in PDA conditions and the effective delivered demand Q_{real} is lower than base demand Q_{BD} and depends on the real head value. There is another value of the head defined as follows:

$$H_{\min} = z + P_{\text{ms}} \tag{2}$$

If the head is below $H_{\min}$, the node demand is zero (Figure 1).

Q_{real} can be calculated as shown:

$$\begin{aligned} &\alpha = 0 && \text{if } H < H_{\min} \\ &\alpha = \left(\frac{H - H_{\min}}{H_{\max} - H_{\min}}\right)^{1/2} && \text{if } H_{\min} < H < H_{\max} \\ &\alpha = 1 && \text{if } H > H_{\max} \end{aligned}$$

In an isolated zone, a subset of shut-off valves operates; therefore, the system topology changes significantly. In order to avoid a real demand Q_{real} that is too low in some nodes, some other isolation valves are necessary.

The proposed methodology allows the definition of the number and location of the additional valves. By analysing the new configurations obtained by activating one or more shut-off valves, some existing and others in addition, and excluding the zone where the burst pipe is located, it is possible to acquire the parameters required to calculate the OF:

$$\text{OF} = \sum_{i=1}^{n_{\text{dist}}} \left(\frac{n_{\text{cv}_i}}{n_{\text{v}}} + \frac{Q_i}{Q_{\text{PDA}_i}} + \frac{Q_{\text{PDA}_i} - Q_{\text{RD}_i}}{Q_{\text{PDA}_i}}\right) w_i \tag{3}$$

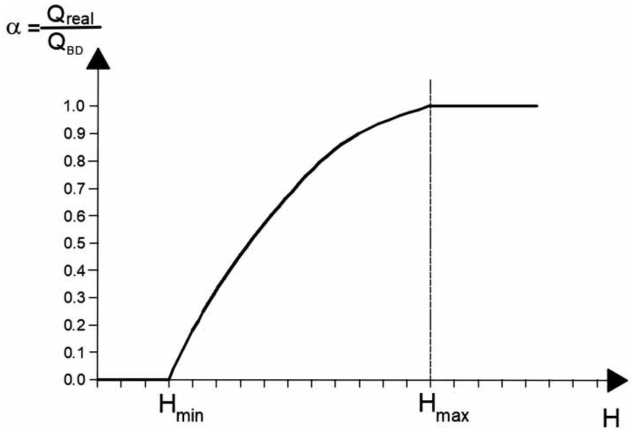

Figure 1 | Value of Q_{real} from each node in the PDA condition.

where:

- n_{dist} is the number of districts of the network;
- n_{CV_i} is the number of operating shut-off valves isolating the district;
- n_{V} is the total number of shut-off valves in the network;
- Q_{PDA_i} is the deliverable demand at each district before the closure of the valves;
- Q_i is the undeliverable demand at each district after the closure of the valves;
- Q_{RD_i} is the deliverable demand at each district after the closure of the valves;
- w_i is the weight for each district calculated as the ratio between the district base demand in DDA (demand driven analysis) conditions and the total base demand in the network.

For each failure scenario, i.e. for each pipe burst, different OF values can be calculated by varying the subset of the activated shut-off valves. The minimum value of OF defines the best subset of valves to isolate the area where the broken pipe is located.

The procedure consists of a two-step approach. The first step aims to define the location of additional shut-off valves and to analyse the number of districts generated in the network. Subsequently, it is necessary to isolate the district where the broken pipe is located, and a new topology is defined. The analysis of the network in PDA conditions provides the parameter to calculate OF for the fixed number of active valves. The solving procedure was implemented in a Matlab environment using an Epanet toolkit (Figure 2).

CASE STUDY RESULTS

The methodology was applied to three real cases, and the results are presented here. Three networks, located in Italy in the Calabrian cities of Praia a Mare, Marano Marchesato and Cosenza, were analysed. The number of users for each network was different; therefore, the methodology was tested in different conditions. Starting from initial conditions characterized by existing valves, each scenario varied because the number of districts increases by adding shut-off valves; when a shut-off valve subset is activated, the topology and the parameters in the network change.

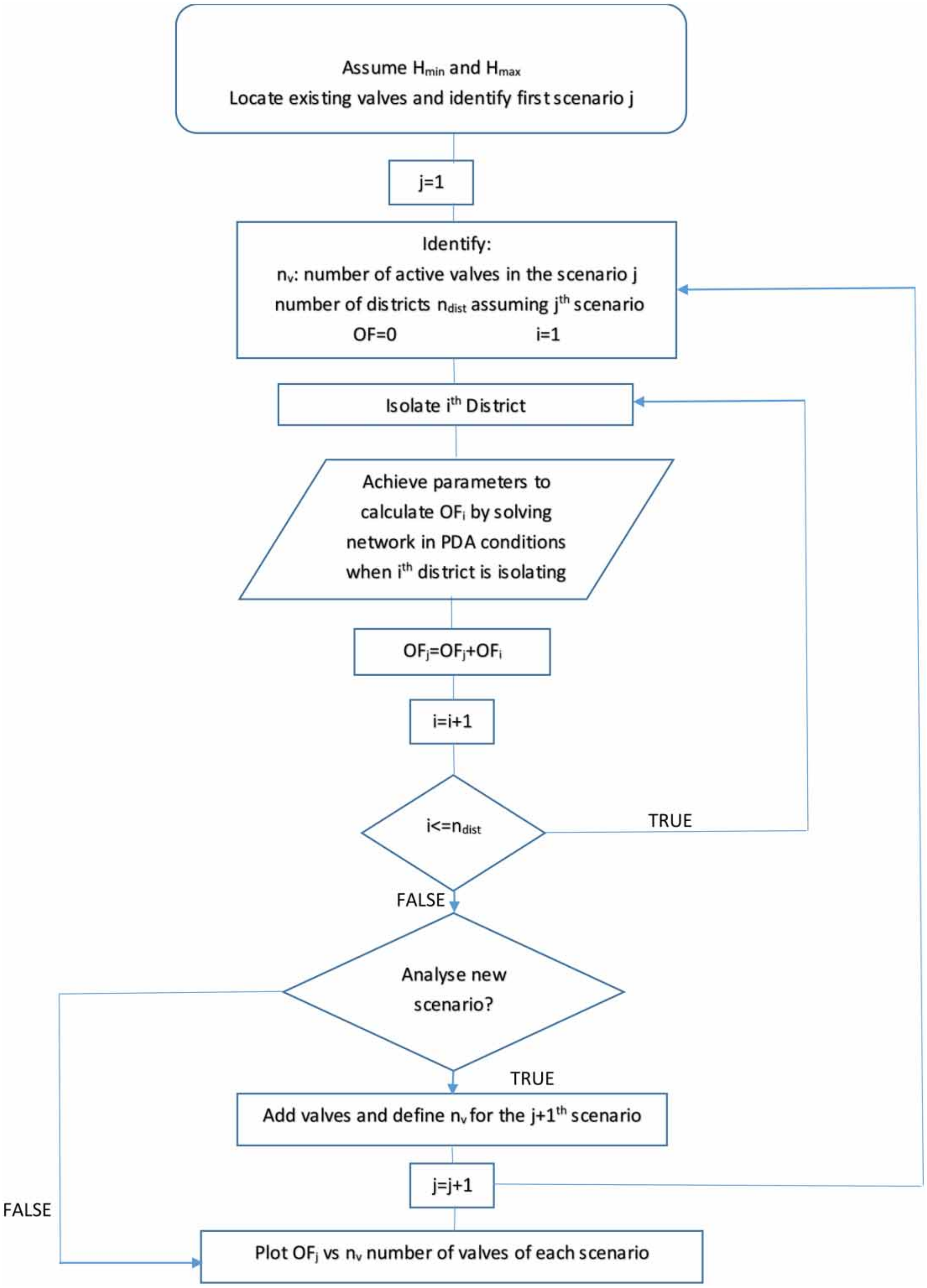

Figure 2 | Procedure to calculate OF.

An analysis of the network with closed valves was performed for each configuration.

The network in Praia a Mare consists of 73 pipes, 53 nodes and two source/tanks of water with a fixed head (Fiorini Morosini *et al.* 2018) and is shown in Figure 3. The total base demand, in summer conditions, is 47.25 l/s. The head H_{max} varies from 29 to 68 m.

In this real network, there are eight shut-off valves. By closing these shut-off valves, it is possible to obtain three districts as shown in Figure 4.

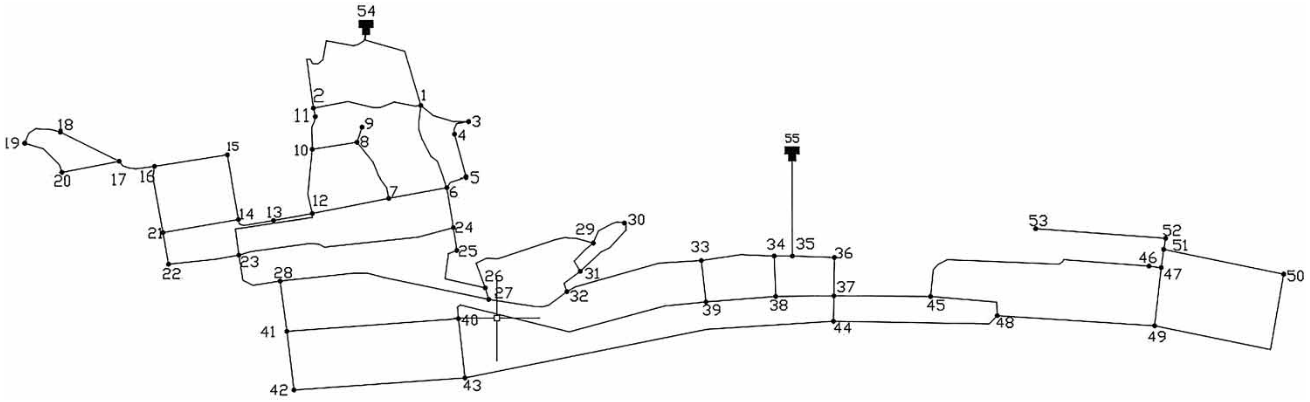

Figure 3 | Network of Praia a Mare (CS, Italy).

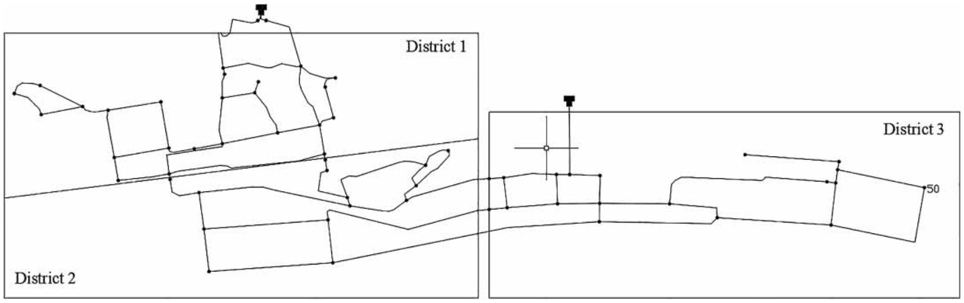

Figure 4 | Initial condition: eight shut-off valves and three districts (Praia a Mare).

Table 1 | Different scenarios obtained with different numbers of shut-off valves (Praia a Mare)

Scenarios	Districts	n_v	Scenarios	Districts	n_v
1	1	3	7	7	16
2	2	6	8	7	17
3	3	8	9	9	22
4	4	9	10	12	26
5	5	12	11	14	30
6	6	14	12	21	38

Different configurations with a defined number of shut-off valves have been considered for the network. In particular, 12 configurations were assumed. By increasing the number of valves in the network, a higher number of districts can be obtained as indicated in Table 1.

For scenario n°6 (see topology in Figure 5), there are 14 valves and six districts.

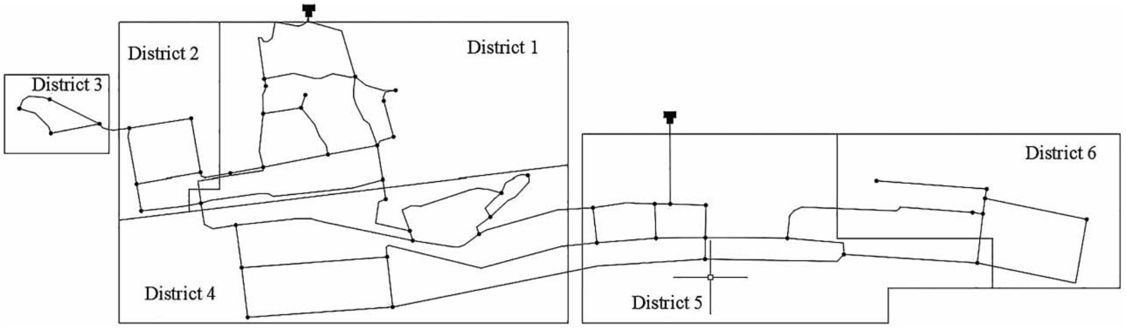

Figure 5 | Scenario n°6: 14 shut-off valves and six districts (Praia a Mare).

Table 2 | Terms to calculate OF for scenario n°6 (Praia a Mare)

District	n_{cv}/n_v	Q/Q_{PDA}	$(Q_{PDA} - Q_{RD})/Q_{PDA}$	w_i	OF_i
1	0.43	0.37	0.38	0.26	0.307
2	0.21	0.11	0.11	0.07	0.031
3	0.07	0.04	0.04	0.04	0.007
4	0.36	0.27	0.27	0.27	0.248
5	0.43	0.35	0.41	0.26	0.311
6	0.21	0.09	0.09	0.09	0.036
				OF	**0.940**

Table 3 | OF values for the different scenarios (Praia a Mare)

Scenario	n_v	OF	Scenario	n_v	OF
1	3	3.000	7	16	0.598
2	6	1.885	8	17	0.643
3	8	1.234	9	22	0.528
4	9	1.167	10	26	0.425
5	12	1.025	11	30	0.342
6	**14**	**0.940**	12	38	0.249

The analysis in PDA conditions provides the parameters for the calculation of the terms of the OF and its value. In this case study, these terms are indicated in Table 2.

In the other cases, the OF value decreases when the number of total valves n_v increases as shown in Table 3 and Figure 6.

The OF failed when the number of valves increased; it then levelled off when the number of valves exceeded a specific value. The solution did not improve significantly when the number of valves reached a threshold. In this way, good results can be achieved also for a limited number of valves. To confirm the results, the methodology was also tested on other WDNs, including those of Marano Marchesato and Cosenza.

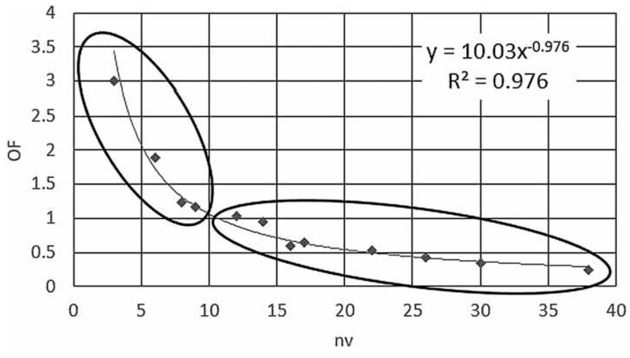

Figure 6 | OF versus the number of shut-off valves n_v (Praia a Mare).

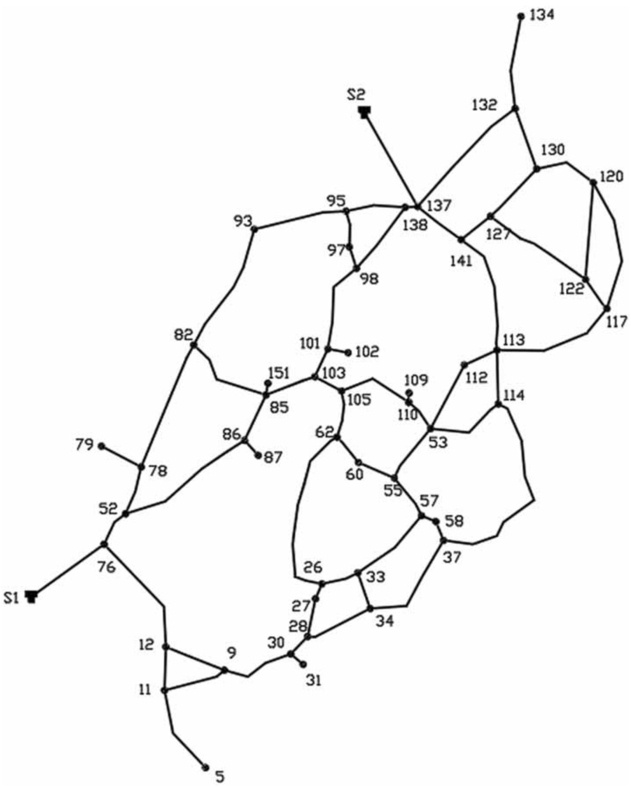

Figure 7 | Network of Marano Marchesato (CS, Italy).

The Marano Marchesato skeletonized network consists of 67 pipes, 52 nodes and two source/tanks of water with a fixed head and is shown in Figure 7. The total base demand is about 2.0 l/s. The head $H_{\max}$ varies from 422 to 435 m.

Table 4 | Different scenarios obtained with different numbers of shut-off valves (Marano Marchesato)

Scenarios	Districts	n_v	Scenarios	Districts	n_v
1	3	8	7	8	16
2	4	9	8	9	18
3	4	10	9	10	21
4	6	12	10	14	26
5	5	13	11	15	28
6	**7**	**14**	12	22	37

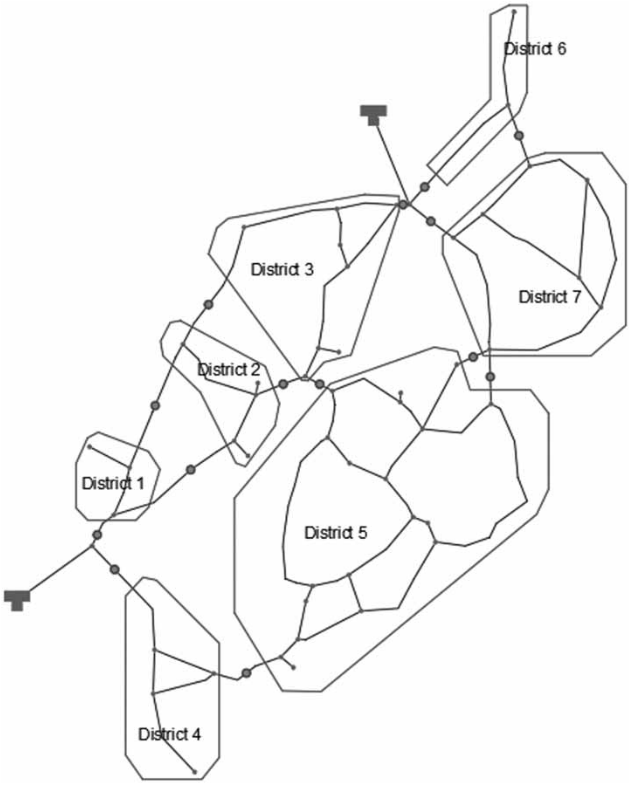

Figure 8 | Scenario n°6: 14 shut-off valves and seven districts (Marano Marchesato).

The different scenarios were obtained by adding further six shut-off valves to the initial 8. Data and topology are shown in Table 4 and Figure 8.

The trend of OF values when the number of valves increases was similar to the previous case. The results are shown in Table 5 and Figure 9.

In all the cases, it is evident that increasing the number of network valves beyond a defined threshold leads to an improvement that is insignificant for technical purposes.

Table 5 | Values of the OF for the different scenarios (Marano Marchesato)

Scenario	n_v	OF	Scenario	n_v	OF
1	8	1.194	7	16	0.702
2	9	1.052	8	18	0.591
3	10	0.974	9	21	0.523
4	12	0.810	10	26	0.371
5	13	0.863	11	28	0.294
6	14	0.722	12	37	0.230

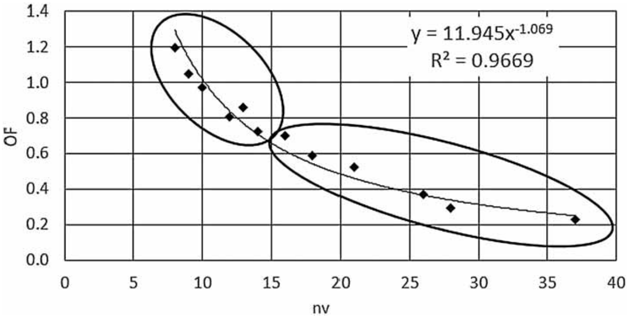

Figure 9 | OF versus the number of shut-off valves n_v (Marano Marchesato).

Finally, the case of the Cosenza network is shown. It is significantly bigger than the other ones; the skeletonized network consists of 48 pipes, 40 nodes and two source/tanks of water with a fixed head. It is shown in Figure 10. The total base demand is about 257 l/s. The minimum head $H_{\max}$ varies from 261 to 339 m.

The scenarios are shown in Table 6.

The OF values when the number of valves changes is shown in Table 7 and Figure 11.

Once the minimum number of valves was defined, the subsequent step was to verify how the solution changes by modifying the position of additional valves.

The OF value for each different position of the additional valves was calculated for the networks in Praia a Mare (six additional valves) and Marano Marchesato (six additional valves).

The results are shown in Table 8 and Figure 12.

In both cases, the different position of additional valves did not significantly change the OF values and the solution can be assumed, for these cases, to be independent from the location of additional valves.

CONCLUSIONS

The use of valves, either existing or added, which are activated whenever a failure occurs, allows the WDN to be managed in emergency conditions. When there is a pipe failure, it is necessary to isolate the area where this pipe is located and suspend service to all users. The extension of the area depends both on the position and on the number of shut-off valves that modify the network topology and influence the head value at each node. In these conditions,

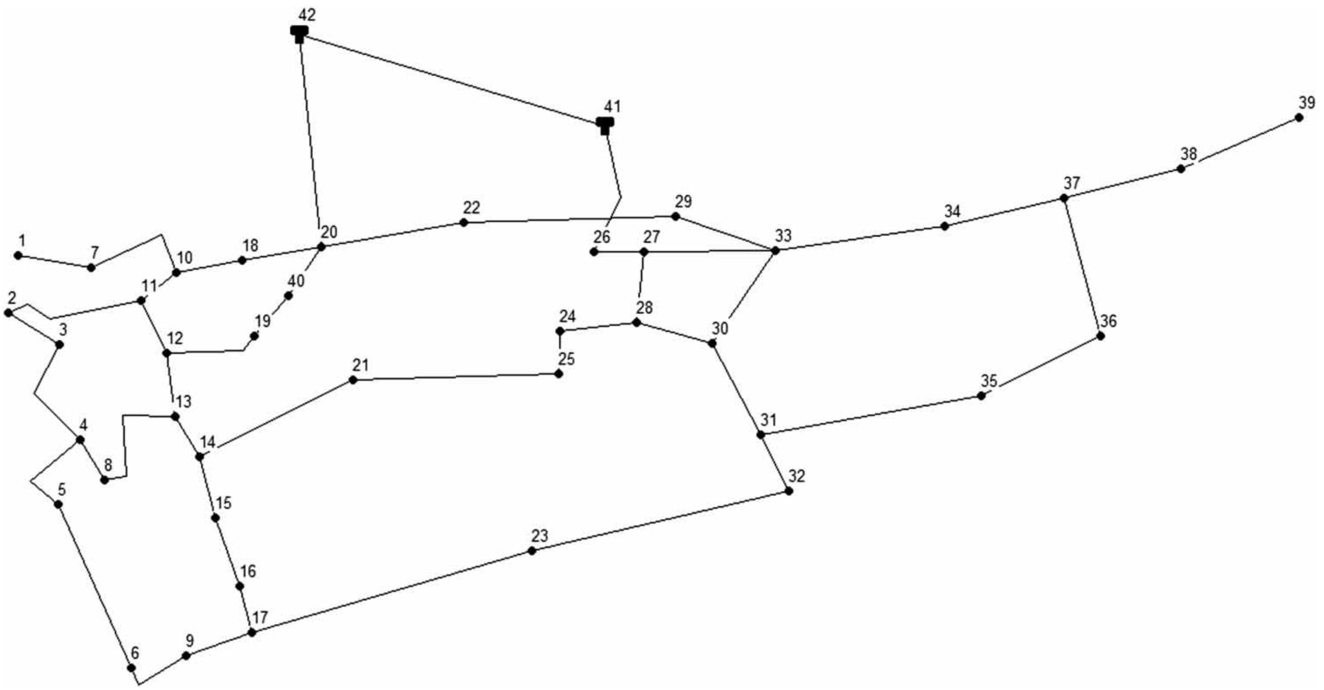

Figure 10 | Network of Cosenza (CS, Italy).

Table 6 | Different scenarios obtained with different numbers of shut-off valves (Cosenza)

Scenarios	Districts	n_v	Scenarios	Districts	n_v
1	11	3	4	25	9
2	15	6	5	29	12
3	20	8	6	30	38

the delivered demand at each node must be determined using a PDA approach and the effective nodal demand is dependent on the real heads.

This paper proposed an approach to define the minimum number of valves to be installed in a real network to

Table 7 | Values of the OF for the different scenarios (Cosenza)

Scenario	n_v	OF
1	3	0.375
2	6	0.289
3	8	0.213
4	9	0.172
5	12	0.140
6	38	0.126

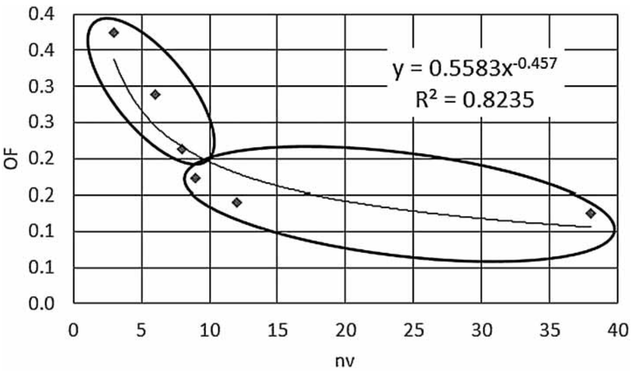

Figure 11 | OF versus the number of shut-off valves n_v (Cosenza).

Table 8 | OF values with different positions of the additional valves

Praia a Mare (six additional valves)		Marano Marchesato (six additional valves)	
ID position	**OF**	**ID position**	**OF**
1	0.940	1	0.722
2	0.817	2	0.644
3	0.760	3	0.520
4	0.733	4	0.626
5	0.759	5	0.547
6	0.785		

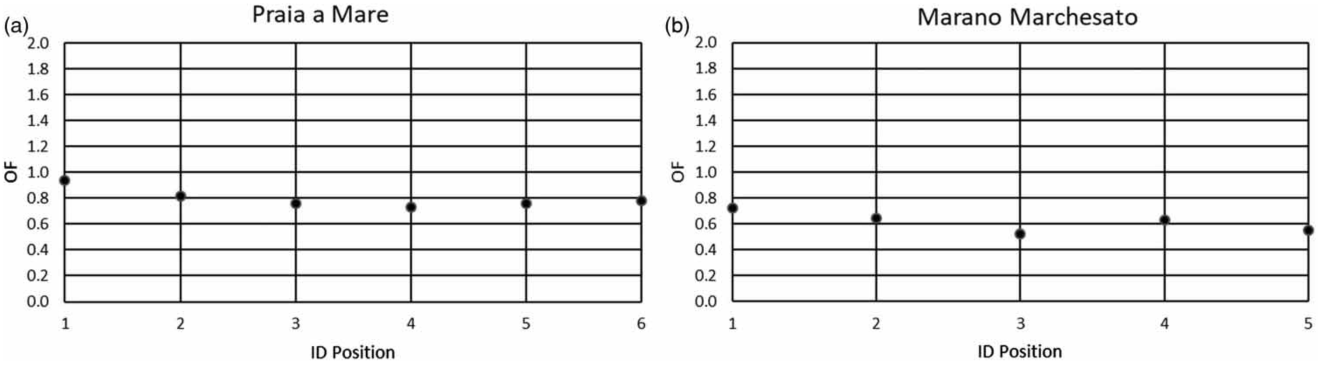

Figure 12 | OF values for different positions of additional valves in Praia a Mare (a) and Marano Marchesato (b).

obtain reliable functioning of the system. This methodology is based on the definition of an OF depending on the input and output hydraulic parameters of the network deriving from a PDA of the system. The procedure was applied to three real cases with the hypothesis of failure conditions. The networks analysed were located in Italy in Praia a Mare, Marano Marchesato and Cosenza, three Calabrian cities with different numbers of inhabitants.

An increase in the number of valves n_v led to a decrease in the OF; therefore, it was possible to determine a value of n_v that represents a threshold beyond which the improvement becomes negligible for technical purposes. Moreover, for the case studies analysed, the results show that the position of additional valves does not significantly change the values of OF and the solution is, for these cases, independent from the location of additional valves. The analysis seems to confirm the results of the proposed methodology. New applications of the methodology will be conducted for the analysis of other real networks and confirm the results.

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