Check for updates

Analysis of the isolation valve system in water distribution networks using the segment graph

A. Simone[1] · C. Di Cristo[1] · O. Giustolisi[2]

© The Author(s) 2022

Abstract

The mechanical reliability of Water Distribution Networks (WDNs) is a relevant technical and scientific issue. During planned maintenance or unplanned interruptions, the affected area must be isolated by valves shutdown. This operation involves the alteration of the network structure, i.e., the domain of the hydraulic system, and for this reason the isolation valve system plays a central role. Some studies started to consider the presence of the isolation valve system in WDNs reliability analysis.

Accordingly, this work uses the Complex Network Theory to analyse the isolation valve system performance and to assess the importance of the segments generated by valves shutdown. Differently from the classic complex network theory approach, in this work the recently proposed WDN-relevance-based betweenness centrality is applied to the segment graph to introduce information about the relevance of the different elements into the network, considering geometric and hydraulic parameters, such as length, demand, risk of disconnection, etc. The proposed strategy also suggests an improvement in the representation of the segment graph with respect to the presence of parallel edges.

The strategy is presented using a small network, while it is demonstrated and discussed using a real WDN. The results indicate that the WDN-relevance-based betweenness centrality allows to effectively assess the importance of the segments generated by valves shutdowns, also providing indications to improve the isolation valve system design.

✉ A. Simone
   antonietta.simone@unina.it

   C. Di Cristo
   cristiana.dicristo@unina.it

   O. Giustolisi
   orazio.giustolisi@poliba.it

1   Department of Civil, Building and Environmental Engineering, University Federico II, Naples, Italy

2   Department of Civil, Environmental, Land, Building Engineering and Chemistry, Technical University of Bari, Bari, Italy

1 Introduction

The Isolation Valve System (IVS) is a crucial element in Water Distribution Networks (WDNs) because it activates segments, i.e., isolated portions of the network, when pipe failures occur, or maintenance is required. During the repair time, the failed pipes are hydraulically isolated from the rest of the network. Shutdown modifies the WDN connectivity structure, then the IVS is closely related to the mechanical reliability of WDNs. This means that for the reliability assessment of WDNs the IVS analysis is mandatory. In many reliability studies, pipe failure is modelled by removing individual pipes from the network, i.e., by assuming the presence of two isolation valves at the ending nodes of each pipe (Walski et al. 2006). This assumption is not quite realistic, because the isolation valves are usually smaller in number and, generally, they are designed to activate segments when one or more pipes need to be repaired. Then the real position of the valves has to be considered in the analysis. Many researchers already studied reliability analysis using graph theory (Jacobs and Goulter 1988; Yazdani and Jeffrey 2011; Gutiérrez-Pérez et al. 2013; Shuang et al. 2014; Agathokleous et al. 2017; Di Nardo et al. 2017; Pagano et al. 2019; Berardi et al. 2022), considering the classic modelling, where links represent pipes and nodes represent vertices. This representation cannot describe the real effect of a pipe failure, since the presence of the IVS entails that many pipes are isolated when failures or ordinary maintenance occur. To account this fact, Walski (1993) introduced a new representation of the network using the segment graph, i.e., a graph where the isolation valves represent the edges, and the vertices represent segments activated by the IVS. Other researchers successively started to analyse the WDNs considering the topology generated by the IVS (Walski et al. 2006; Jun and Loganthan, 2007; Creaco et al. 2010; Giustolisi and Savic 2010; Alvisi et al. 2011; Liu et al. 2017; Atashi et al. 2020).

Recently, various approaches, mainly based on topological analysis and tools proposed by the Complex Network Theory (CNT), have been adopted to evaluate the influence of the IVS in various applications. Huzsvár et al. (2019) proposed the WDNs classification using the segment graph; while Zischg et al. (2019) proposed a methodology for studying WDNs reliability and valve placement assessment by using network topology and IVS information. Wéber et al. (2020) proposed a novel methodology based on a topological metric that allows to individuate the critical segments in WDNs. The metric allows to determine the distributions of the vulnerability of both the segments and of the whole network against a single failure. Giustolisi (2020) mathematically demonstrated that the reliability of WDNs depends on the IVS, which influences the domain of the system, and on the hydraulic capacity of the part of the system still connected after the closures. The author also indicated that an optimal design of the IVS with respect to the topology minimizes the risk of disconnections related to the segments. Hernandez Hernandez and Ormsbee (2021a) proposed a methodology to evaluate the impact of valve locations when evaluating the performance of WDNs, in terms of loss of connectivity and reduction in demand satisfaction under a failure condition. Furthermore, the authors also evaluated the fire requirements in combination with a segment-based reliability assessment. Hernandez Hernandez and Ormsbee (2021b) proposed a procedure to identify segment elements and unintended isolations resulting from valves shutdowns. Abdel-Mottaleb and Walski (2021) developed a method based on graph theory to visualize the segment-valve topology and to identify the most important and vulnerable segments through the construction of the reachability matrix. This matrix provides

values of the index of importance for each segment, indicative of the number of unintended isolations caused by its closure. Higher index values indicate greater damages resulting from the closure. Furthermore, in the presence of failed valves, they proposed the modification of the segment graph in order to topologically reorganize the network using the degree metric. Then, Hernandez Hernandez and Ormsbee (2022) proposed a heuristic method to improve the distribution of existing IVSs to minimize the number of valves required to isolate any individual segment. The method takes advantage of graph theory concepts and is based on an algorithm that provides a trade-off between the increase of valve number and the unsupplied demand resulting from disconnected segments.

The above-described works do not consider the relevance of the different elements of the network with respect to the presence of strategic structures (e.g., schools, hospitals, etc.), source nodes (e.g., reservoirs, tanks) and specific hydraulic devices (e.g., pumps). All segments have the same relevance and their importance is evaluated only considering their topological features. For example, using classical CNT tools, segments with many connections with other segments present a high topology-based centrality, while segments with a low number of connections present a low centrality even if they are characterized by a great relevance (e.g., segment close to the reservoirs). In this latter case, the CNT tools do not correctly quantify the actual importance of the segments, which, instead, can be considered integrating the information about the intrinsic relevance of the elements. The idea of assigning an intrinsic relevance to the vertices of complex networks has been proposed by Giustolisi et al. (2020), which tailored some classic CNT centrality metrics (degree, harmonic, betweenness and edge betweenness) embedding the information about the intrinsic relevance of vertices to account for their different role in the network. They applied the strategy to social networks and WDNs to test its effectiveness.

The aim of this work is to analyse the IVS performance by assessing the importance of the segments generated by valves shutdown using the graph theory. The original contribute of the work is represented by a new way to analyse the IVS by applying the WDN-relevance-based betweenness centrality (Giustolisi et al. 2020) to the network segment graph. In fact, the main novelty is the use of a tailored metric, which allows to embed the relevance of the segments (e.g., risk of disconnection, demand, etc.) with the topological information. In this way, the role of the structure and the characteristics of the system are considered in the assessment of the importance of the segments generated by valves shutdowns. The strategy also adopts a new approach for manage parallel edges in the segment graph in presence of many isolation valves between the same segments.

The presented work compares the performances of the analysis when adopting the WDN-relevance-based betweenness centrality respect to the use of the classic betweenness. The result of the analysis rank segments by importance, which is useful to suggest possible actions (e.g., maintenance planning) to increase the network reliability (e.g., indicating the most critical segment whose closure would cause more damage to the system) and to indicate whether the IVS functional.

The paper is organized as follows. The Sect. 2 describes the segment graph proposed for WDNs; the Sect. 3 recall the WDN-relevance-based betweenness centrality here used for the segment graph analysis and includes a comparison between the effectiveness of the classic metric and the tailored one in classifying the segments considering a schematic network; the Sect. 4 presents the proposed segment graph analysis applied to a real WDN. Concluding remarks are drawn in the last section.

2 Segment graph representation and parallel pipes

WDNs are urban infrastructures composed of interconnected elements. When failure events or maintenance of pipes occur, the presence of the IVS guarantees the closure of only a portion of the network, permitting the operation of the remaining part of the system, i.e., the IVS works by activating useful segments to avoid the interruption of the whole system. For a reliable analysis of the IVS, the network representation must refer to the segment graph, where the vertices represent segments, i.e., the group of nodes and pipes activate by the valve closure, and the isolation valves connecting them are the edges. To avoid confusion, nodes/ pipes are used when referring to the elements of WDNs and edges /vertices when referring to the segment graph. Edges correspond to the isolation valves positioned in correspondence of pipes and vertices correspond to the segments of the real WDNs, respectively.

The proposed segment graph procedure is described considering the schematic Apulian network (Giustolisi et al. 2020), reported in Fig. 1-a. For simplicity, in the Fig. 1 the IVS is assumed composed of three isolation valves, which active the three segments identified by the different colors, i.e., they divide the network into 3 portions. Segments containing a single node, as reservoir represented by the segment S_1, are defined node-segment, while segments containing a single pipe or various pipes and nodes (e.g., segments S_2 and S_3) are defined pipe-segments. The segment graph of Apulian network is characterized by a set of vertices S_n (with $n=3$) and a set of edges E_l (with $l=3$) that represents the links connecting them (Fig. 1-b). In the segment graph each vertex can be connected to several edges, while each edge can be connected with at most two vertices.

It is possible the presence of parallel edges in the segment graph, due to the presence of isolation valves at the boundary between the same segments, as shown in the example in Fig. 1. In fact, the vertices S_2 and S_3 are connected to each other through two edges in the segment graph (the two valves V_2 and V_3 in the WDNs). Both edges allow the path from S_2 to S_3, and *vice versa*, then to isolate the vertex S_2 is necessary to close both valves. Since more edges indicate a greater probability of reaching the ending segment-vertices (double
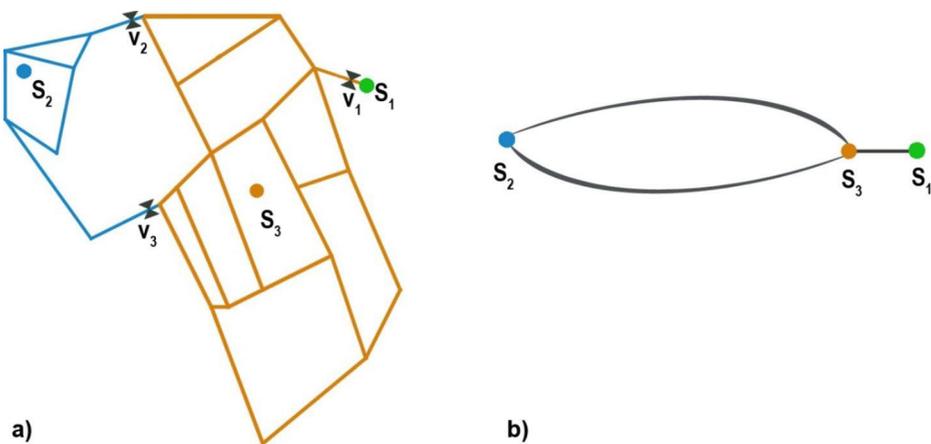

Fig. 1 Generation of the segment graph in Apulian WDN (a). Segment graph composed of three segments and three edge connecting them (b)

in Fig. 1), in the presented analysis the weight of the edge is reduced (halved in the example case) when betweenness is computed. In general, the proposed strategy intervenes on the weight of the single edge during the simulation, i.e., it decreases the weight of the edge, generally unitary, in an inversely proportional way to the number of edges available to get from vertex to vertex.

3 WDN-Relevance-based betweenness centrality for the segment graph analysis

The concept of centrality has recently become fundamental in the analysis of networked systems. The betweenness centrality is one of the most common centrality metrics used in network analysis (Freeman 1977). It detects the vital points of the network, which maintain the connections by ensuring that the flow goes from one vertex to the other. The metric is computed counting how many times an element is traversed by shortest paths between two vertices in the network, i.e., quantifying how an element intervenes in the information transfer. The vertex with the most strategic location, i.e., with the highest metric value, is the most important. The standard betweenness centrality is defined as:

$$B\left(v\right) = \sum\nolimits_{s \neq v \neq t \in N} \frac{\sigma_{s,t}\left(v\right)}{\sigma_{s,t}} \tag{1}$$

where $\sigma_{s,t}$ are all shortest paths between pair of vertices s and t, $\sigma_{s,t}(v)$ are all shortest paths between pair of vertices s and t crossing node v and N is the number of vertices (v, s, $t=1$, …, N).

The standard formulation of the betweenness centrality represents very well the topological component of the system, without account for the different relevance of the elements, i.e., how the different role of the vertices (i.e., segments) intervenes in the analysis. With reference to the segment graph analysis, this implies that the betweenness centrality of a vertex crossed by paths between very relevant vertices (e.g., high demand, high risk of disconnection, etc.) does not integrate this information in the analysis, although this aspect has a high impact on the operation of the system, particularly when a failure event occurs.

Whit the purpose to enhance the analysis of complex systems, the standard betweenness centrality has been recently tailored (Giustolisi et al. 2020) to embed the intrinsic relevance of vertices. In this way, the potential of the metric to assess the importance of elements increases. The WDN-relevance-based betweenness centrality is computed considering that each traversed vertex increases of a quantity $f\left(R_s, R_t\right)$ as:

$$B\left(v\right) = \sum\nolimits_{s \neq v \neq t \in N} f\left(R_s, R_t\right) \frac{\sigma_{s,t}\left(v\right)}{\sigma_{s,t}} \tag{2}$$

where the function $f(R_s, R_t)$ depends on the intrinsic relevance of the ending vertices s and t of the generic edge l. The intrinsic relevance R_n ($n=1$, …, N) of each vertex depends on the type of network and on the analysis to perform. For WDNs analysis, it is assigned using the segment features (e.g., unsupplied demand, risk of disconnection, etc.). The relevance of pipe-segments corresponds to the sum of the relevance of all nodes belonging to the seg-

ment, while the relevance of node-segments (water sources, such as reservoir, tank, etc.) corresponds to the sum of the relevance of the nodes belonging to the portion of the network influenced by them (Giustolisi et al. 2019). The presented analysis is performed using the function $f(R_s, R_t) = (R_s+R_t)/2$, corresponding to the mean value of the intrinsic relevance of the ending vertices s and t. This function correctly highlights the role of the intrinsic relevance in the paths between vertices.

In the presented study the intrinsic relevance is assumed equal to the disconnection risk, computed as the product of the probability of failure of each segment, proportional to the pipe length, and the damage deriving from the impossibility of supplying the required water to consumers (Giustolisi 2020). The WDN-relevance-based betweenness centrality thus formulated is then applied to the segment graph of WDNs to rank the vertices according to both their relevance and topological position.

Considering the WDN-relevance-based betweenness, the vertices with higher values are those traversed more times by shortest paths between relevant vertices. Therefore, the intrinsic relevance of the vertices enriches the information of the metric, beyond just the network topology, and allows to identify the segments that are important because located in the main paths and with a greater risk of disconnection, i.e., the rankings importance of a segment increases when it is traversed by shortest paths involving segment-vertices characterized by greater intrinsic relevance.

The comparison among the classic betweenness and the WDN-relevance-based betweenness is realized considering the Apulian network, because in this simple scheme the knowledge of the operating conditions permits to evaluate the performances of the different analyses. The Apulian network with the complete IVS is illustrated in Fig. 2-a. Fig. 2-b and 2-c report the relative segment graph, characterized by a set of 6 vertices and a set of 7 edges connecting them.

Figure 3 reports the classic betweenness centrality (Fig. 3a) and the WDN-relevance-based betweenness centrality (Fig. 3b) applied to the segment graph of Apulian network. The network is divided into segments of different colours, which indicate the value of the metric for the specific segment. The metric values are represented by 22 intervals ranging
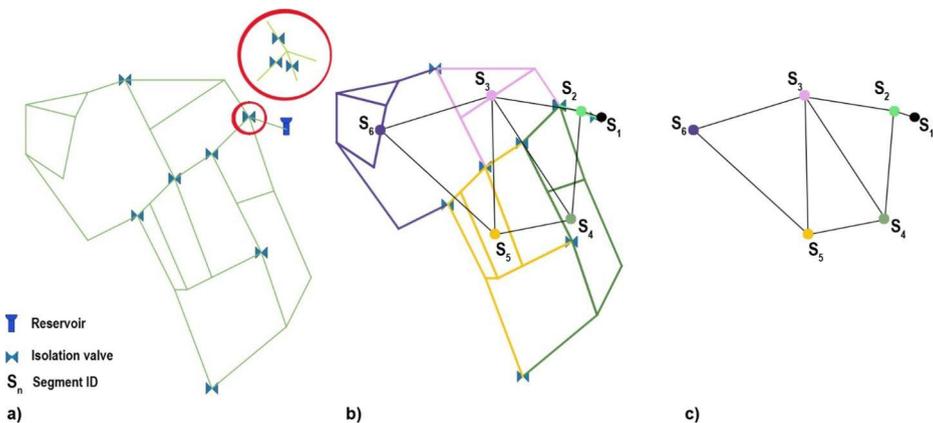

Fig. 2 Apulian layout with IVS (a). Segments generated by the IVS in Apulian WDN (b). Segment graph of Apulian WDN (c)
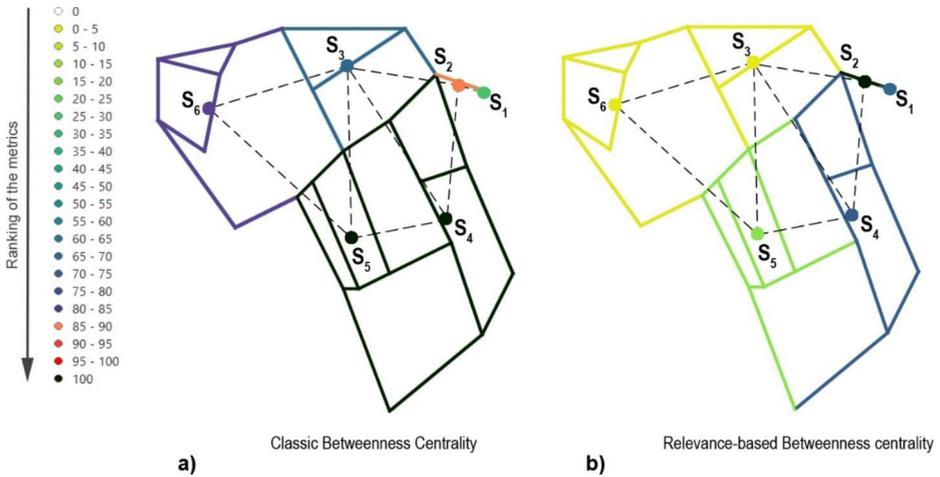
Fig. 3 Classic betweenness centrality (a) and WDN-relevance-based betweenness centrality (b) for the segment graph of Apulian network

from the minimum value (0) to the maximum value (100). Computing the classic betweenness centrality, with the assumption of identical intrinsic relevance of vertices (i.e., equal to 1), the ranking of values shows that the metric fails in identifying the importance of the segments (Fig. 3a). In fact, the metric assigns greater importance to the segments distant from the reservoir, i.e., vertices S_4 and S_5, than to those close to it, i.e., vertices S_1 and S_2. This result is somewhat unrealistic from a technical point of view, because all the paths from the source of water (node-segment S_1) always traverse the segment S_2 to distribute the water to the entire system. i.e., the fact that the segment S_2 has less importance respect other segments in the network is not consistent with the hydraulic operation of the system. Differently, the WDN-relevance-based betweenness centrality (Fig. 3b), embedding information on the intrinsic relevance of the segments as risk of disconnection, correctly reflects the operation of the system, assigning greater importance to the segments include the reservoir (node-segment S_1) and those close to it (S_2), consistently with the hydraulic engineering knowledge, particularly in the perspective of failure events. Conversely, the other segments, being traversed by a smaller number of shortest paths and having a lower intrinsic relevance, have lower metric values.

These results show how the WDN-relevance-based metric is able to provide information on the risk of disconnection in the network, ranking the segments respect their importance in evaluating the mechanical reliability of the system. Furthermore, such an analysis is also useful in assessing whether the IVS has been well designed. For example, segments with high risk of disconnection not located in topologically strategic positions or close to water sources, indicate a non-optimal IVS design. In this case, the analysis supports the reliability of the system, providing indications on where to intervene (e.g., suggesting the addition of pipes to split segments) to limit the damage when a failure event occurs in one of the high-risk segments.

4 Real case study

The relevance-based betweenness centrality is here applied to the segment graph of a real WDN located in a municipality in southern Italy (metropolitan city of Bari), which covers an area of approximately 75 km² and with 8.461 inhabitants. The layout of the network and of the IVS is reported in Fig. 4. The network model is composed of one reservoir, 644 pipes, 528 nodes and 381 isolation valves. In addition, the network contains 5 closed valves.

Figure 5 reports the 243 segments generates by the IVS, which are identified by different colours. The one relative to the water source is a node-segment. The "actual" positions of the demands in the network are indicated by small black dots.

To each segment it is assigned a value of intrinsic relevance equal to the risk of disconnection, as product of the pipe length of the segment (probability of failure) and the unsupplied demand (damage). The sum of the demand for each segment corresponds to the "actual" demand that can be supplied to the users.

Appling the proposed strategy, the relative segment graph is built and the WDN-relevance-based betweenness centrality computed. Each segment corresponds to a vertex,

Fig. 4 Real WDN layout with its IVS
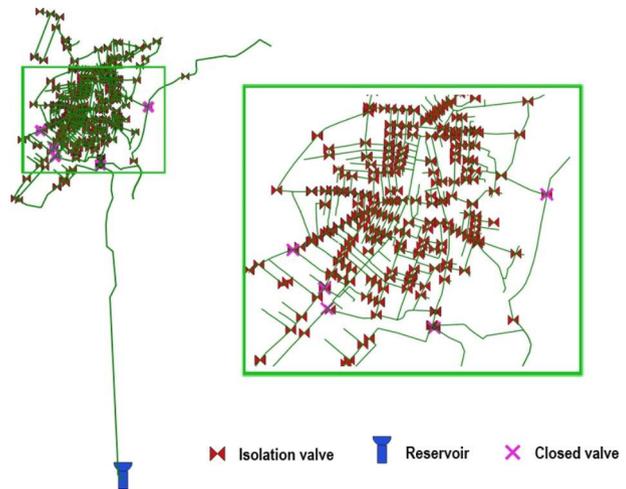
Fig. 5 Real WDN layout with user locations (black dots) and segments activated by IVS (different colors)
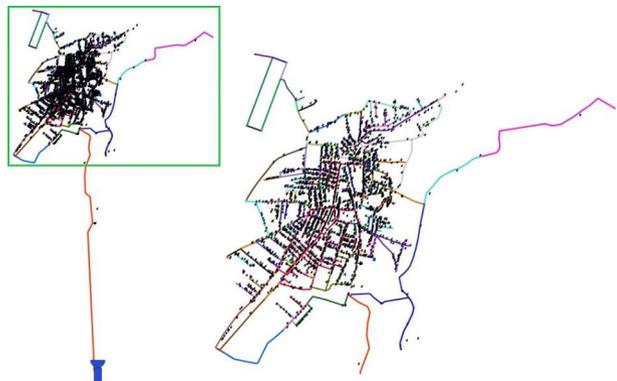
located in its barycentric position, indicated by circles in Fig. 6. The metric values for the various segments identified by the IVS are normalized in the range 0-100. The colour of the circles in Fig. 6 indicates the metric values of the vertices, which are divided into the 22 intervals reported on the right of the figure. The majority of segments have metric values between 0 and 10, while few have values greater than 65. This result indicates that there are few important segments in the system, i.e., they represent a minority compared to the total number of segments. Some of them intercept/contain the main pipes (i.e., the skeleton of the system) and are in the paths from the reservoir towards the entire network. However, there is a portion of segments that have high metric values although not holding hydraulically important positions. In this case, they are important because critical, i.e., the high values of the metric are due to their large size in the network (and therefore high risk). This situation may be the result of non-optimal design of the IVS. The presence of many segments with low metric values indicates a high reliability of the network because their interruption doesn't considerably affect the system operation. Furthermore, the intense meshing of the WDNs supports the presence of many alternative pathways, which increase the resilience of the system with respect to most of the segments when they do not intercept the main distribution water paths.

The comparison between the standard and the WDN relevance-based metric is shown in Fig. 7. In order to highlight only the most relevant aspects of the analysis, only the segments with values of the metric greater than 10 are reported. The standard metric (Fig. 7a) highlights the topologically most strategic segments as the most important, i.e., those most crossed in the paths between segments in the system, without considering the specific relevance of each one. As a result, the most important segments are positioned in the central and upper part of the network, while other vertices with average importance are positioned at the entrance of the distribution system. This result does not correctly identify the importance of the segments according to what the hydraulic engineering knowledge suggests, i.e., that the segments close to the reservoirs are the most important.

The metric based on relevance (Fig. 7b), on the other hand, indicates as the most important the segments located downstream of the adduction pipeline, i.e., those at the entrance of the distribution system located in red circle. These results indicate that the metric captures the most important hydraulic components, i.e., the closure of one these segments considerably affects the system operation. The WDN relevance-based betweenness centrality also highlights other segments located in the central and high part of the network as average

Fig. 6 WDN-Relevance-based betweenness centrality for the segment graph of Real WDN
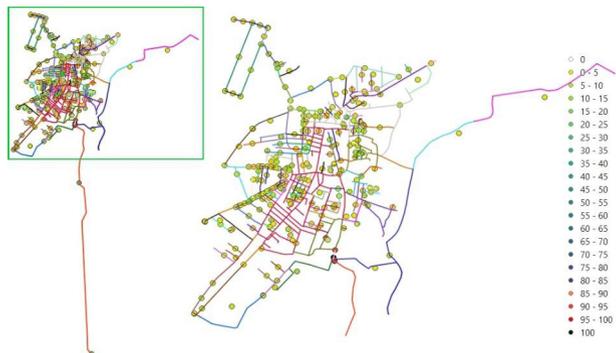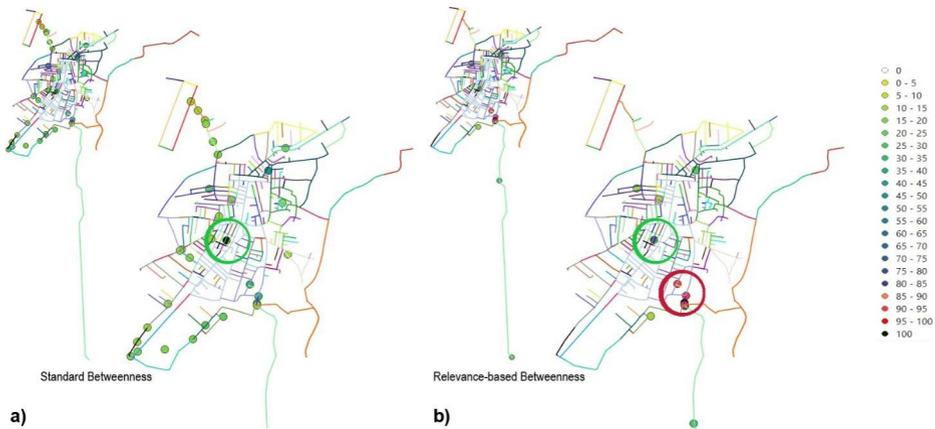
Fig. 7 Standard betweenness centrality (a) and WDN relevance-based betweenness centrality (b) for the segment graph of Real WDN. Green circle highlights a segment important for both metrics, red circle highlights the most important segments for WDN relevance-based betweenness centrality. Figure only reports values of the metric greater than 10

important. In particular, the segment positioned in the central part of the network, highlighted by the green circle, assumes importance for both the metrics. Its importance is due to the topological position, which is strategic in the network, and which is matched by both metrics, and to its high risk of disconnection.

Figure 8a highlights in the black circle a segment individuated by the WDN relevance-based betweenness centrality with a high importance. As shown in the particular of Fig. 8c, the vertex that represents it in the segment graph is indicated with a dot, placed in its barycentric position, and the colour corresponds to the value of the WDN relevance-based betweenness centrality that the segment assumes. The high value of the metric for this segment, so far from the reservoir, is due to its high risk of disconnection for its large extension, as show the zoom of Fig. 8b, and to the high number of users (high consumers demand) belonging to it. This is indicative of a not optimal design of the IVS for the network. In fact,

Fig. 8 WDN relevance-based betweenness centrality for the segment graph of the real WDN. Black circle (a) highlights a segment that is important for its high risk of disconnection. Zoom of the area in the circle (b), zoom of the segment (c)
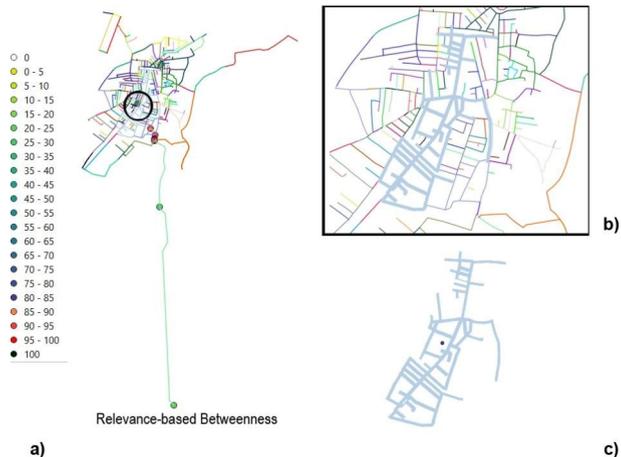
a well-designed IVS must ensure that critical segments in the system have to be positioned in hydraulically strategic positions, i.e., close to the reservoirs. The presence of such large segments, especially if very connected to other areas of the system, could cause many inconveniences in case of closure due to failures or maintenance.

Obviously, the case of the segment representing the system's adduction pipeline is different. In fact, for this segment, the high value of the WDN relevance-based betweenness is due to the proximity of the segment to the reservoir (and therefore to the number of times that the segment is crossed in the paths between very important segments), rather than to a high value of the risk of disconnection intrinsic to the segment itself, considering that the number of users belonging to it is very low.

Figure 9 compares the results of both metrics, illustrating only vertexes with metric values greater than 20. The red circles (Fig. 9a, b) indicate a segment that results important for both the metrics, even if with different order of magnitude. The zoomed green box (Fig. 9c) indicates that it is connected to many other segments, hence its topological importance in the paths, and at the same time, for its large extension and the large number of connected users, it has a high risk of disconnection, hence a high hydraulic importance.

The performed analyses showed the effectiveness of the WDN relevance-based betweenness centrality metric in identifying the most important segments in the system with respect to the risk of disconnection. It highlights that the segment importance can arise from several factors: (i) proximity to water sources, (ii) topologically strategic position and (iii) high risk
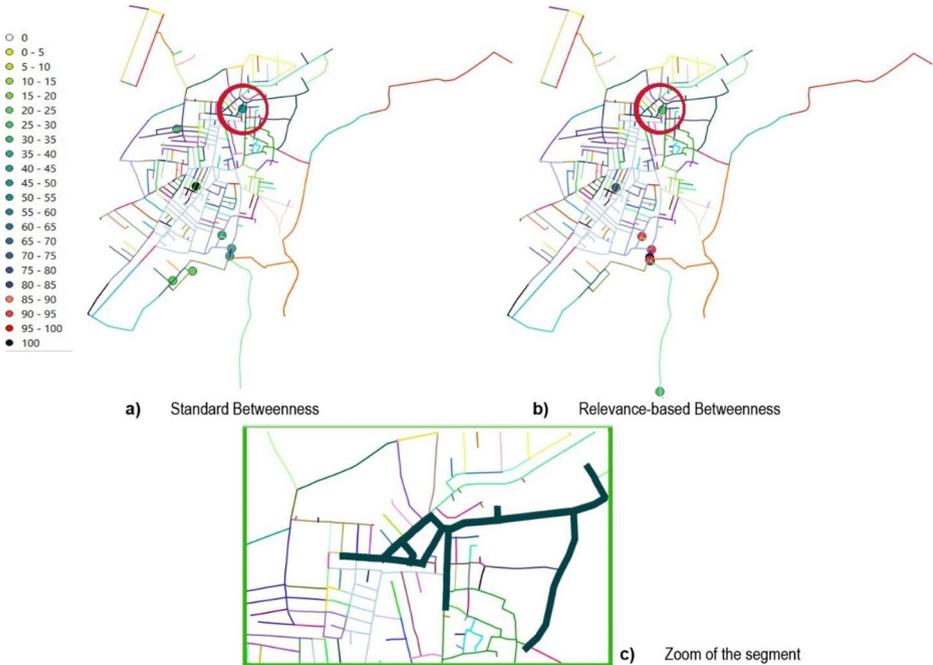

Fig. 9 Standard betweenness centrality (a) and WDN relevance-based betweenness centrality (b) for the segment graph. Red circle highlights a segment that is important for both metrics. Zoom of the segment (c)

of disconnection. This last factor is high for large segments very connected to the various areas of the network, indicative of a non-optimal design of the IVS.

The strategy also provides valid indications on possible activities aimed to improve the IVS and, therefore, the reliability of the system. High metric values can suggest a density of isolation valves in WDNs lower than the desirable level, and then addition of new valves is necessary. In other cases, it can indicate that their position is not optimal, and a new displacement could be sufficient to improve the system operation. The proposed analysis supports these interventions.

5 Conclusions

This work proposes the analysis of the IVS of WDNs using the network segment graph, improved with respect to the presence of parallel edges. Moreover, the proposed analysis uses the WDN relevance-based betweenness centrality metric, which, respect the classic metric, integrates topological information with the relevance of the segments (e.g., risk of disconnection).

The analysis provides categories of importance of the segments. The importance increases with the number of shortest paths involving segment-vertices characterized by high intrinsic relevance. Segments with high values of the metric have the highest impact on WDN when failure or planned maintenance occur.

Results show that the WDN relevance-based betweenness centrality is very effective in analysing the segments, highlighting that the segment importance can arise from multiple factors, such as proximity to water sources, strategic position in the network and too large risk of disconnection of the segments. From this point of view, the analysis is also useful in providing indications on actions aimed at improving the IVS design, and therefore, the network reliability.

Ethics declarations

Conflict of Interest The authors have no Conflicts of Interest/ competing interests to declare that are relevant to the content of this article.

References

Abdel-Mottaleb N, Walski T (2021) Evaluating Segment and Valve Importance and Vulnerability. J Water Resour Plan Manag 147(5). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001366

Agathokleous A, Christodoulou C, Christodoulou SE (2017) Topological Robustness and Vulnerability Assessment of Water Distribution Networks. Water Resour Manage 31:4007–4021. https://doi.org/10.1007/s11269-017-1721-7

Alvisi S, Creaco E, Franchini M (2011) Segment identification in water distribution systems. Urban Water 8(4):203–217. https://doi.org/10.1080/1573062X.2011.595803

Atashi M, Ziaei AN, Khodashenas SR, Farmani R (2020) Impact of isolation valves location on resilience of water distribution systems. Urban Water Journal 17:560–567. https://doi.org/10.1080/1573062X.2020.1800761

Berardi L, Laucelli D, Ciliberti F, Bruaset S, Raspati G, Selseth I, Ugarelli R, Giustolisi O (2022) Reliability analysis of complex water distribution systems: the role of the network connectivity and tanks. J Hydroinformatics 24(1):128–142. https://doi.org/10.2166/hydro.2021.140

Creaco E, Franchini M, Alvisi S (2010) Optimal Placement of Isolation Valves in Water Distribution Systems Based on Valve Cost and Weighted Average Demand Shortfall. Water Resour Manage 24:4317–4338. https://doi.org/10.1007/s11269-010-9661-5

Di Nardo A, Di Natale M, Giudicianni C, Musmarra D, Rodriguez Varela JM, Santonastaso GF, Simone A, Tzatchkov V (2017) Redundancy features of water distribution systems. Procedia Eng 186:412–419. https://doi.org/10.1016/j.proeng.2017.03.244

Freeman LC (1977) A set of measures of centrality based on betweenness. Sociometry 40(1):35–41. https://doi.org/3033543

Giustolisi O (2020) Water Distribution Network Reliability Assessment and Isolation Valve System. J Water Resources Planning and Management 146(1):04019064. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001128

Giustolisi O, Savic DA (2010) Identification of segments and optimal isolation valve system design in water distribution networks. Urban Water Journal 7(1):1–15. https://doi.org/10.1080/15730620903287530

Giustolisi O, Ridolfi L, Simone A (2020) Embedding the intrinsic relevance of vertices in network analysis: the case of centrality metrics. Nat Sci Rep 10:3297. https://doi.org/10.1038/s41598-020-60151-x

Gutiérrez-Pérez JA, Herrera M, Pérez-García R, Ramos-Martínez E (2013) Application of graph-spectral methods in the vulnerability assessment of water supply networks. Math Comput Model 57(7):1853–1859. https://doi.org/10.1016/j.mcm.2011.12.008

Hernandez Hernandez E, Ormsbee L (2021b) Segment-Based Assessment of Consequences of Failure on Water Distribution Systems. J Water Resour Plan Manag 147(4). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001340

Hernandez Hernandez E, Ormsbee L (2021a) Segment Identification Procedure for Water Distribution Systems. J Water Resour Plan Manag 147(5). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001363

Hernandez Hernandez E, Ormsbee L (2022) A Heuristic for Strategic Valve Placement. J Water Resour Plan Manag 148(2). https://doi.org/10.1061/(ASCE)WR.1943-5452.0001497

Huzsvár T, Wéber R, Hős C (2019) Analysis of the Segment Graph of Water Distribution Networks. Periodica Polytech Mech Eng 63(4):295–300. https://doi.org/10.3311/PPme.13739

Jacobs P, Goulter IC (1988) Evaluation of methods for decomposition of water distribution networks for reliability analysis. Civil Eng Syst 5(2):58–66. https://doi.org/10.1080/02630258808970505

Pagano A, Sweetappl C, Farmani R, Giordano R, Butler D (2019) Water Distribution Networks Resilience Analysis: a Comparison between Graph Theory-Based Approaches and Global Resilience Analysis. Water Resour Manage 33:2925–2940. https://doi.org/10.1007/s11269-019-02276-x

Jun H, Loganathan GV (2007) Valve-Controlled Segments in Water Distribution Systems. Journal of Water Resources Planning and Management 133(2). https://doi.org/10.1061/(ASCE)0733-9496(2007)133:2(145)

Liu H, Walski T, Fu G, Zhang C (2017) Failure Impact Analysis of Isolation Valves in a Water Distribution Network. J Water Resour Plan Manag 143(7):04017019. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000766

Shuang Q, Zhang M, Yuan Y (2014) Node vulnerability of water distribution networks under cascading failures. Reliab Eng Syst Saf 124:132–141. https://doi.org/10.1016/j.ress.2013.12.002

Walski TM (1993) Water distribution valve topology for reliability analysis. Reliab Eng Syst Saf 42(1):21–27. https://doi.org/10.1016/0951-8320(93)90051-Y

Walski TM, Weiler JS, Culver T (2006) Using Criticality Analysis to Identify Impact of Valve Location. 8th Annual Water Distribution Systems Analysis Symposium, Cincinnati, Ohio, USA, August 27–30. https://doi.org/10.1061/40941(247)31

Wéber R, Huzsvár T, Hős C (2020) Vulnerability analysis of water distribution networks to accidental pipe burst. Water Res 184:116178. https://doi.org/10.1016/j.watres.2020.116178

Yazdani A, Jeffrey P (2011) Complex network analysis of water distribution systems. Chaos 21(1):016111. https://doi.org/10.1063/1.3540339

Zischg J, Reyes-Silva JD, Klinkhamer C, Krueger E (2019) Complex Network Analysis of Water Distribution Systems in Their Dual Representation Using Isolation Valve Information. World Environmental and Water Resources Congress 2019 https://doi.org/10.1061/9780784482353.046