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Key Points:

- A novel approach to analyze the Isolation Valve System (IVS) of water distribution networks (WDNs) ranking the importance of isolation valves and segments
- Application of the WDN-tailored betweenness of the complex network theory as ranking metric
- Global analysis of the IVS could be useful to easily identify the most critical valves and segments and consequently to retrain the IVS

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A Novel Approach to Analyze the Isolation Valve System Based on the Complex Network Theory

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Abstract Complex Network Theory (CNT) studies network models and centrality metrics to deal with reliability/vulnerability assessment in networked systems. Classic CNT analyses evaluate the impact of failure of single vertices/edge elements on system connectivity assuming that all vertices/nodes have the same relevance. In Water Distribution Networks (WDNs), the Isolation Valve System (IVS) plays a crucial role for system reliability because a pipe failure asks for valves shutdown to isolate that pipe, usually requiring the isolation of a larger network segment, having its intrinsic relevance. This circumstance makes classic connectivity analyses and metrics of CNT misleading in reliability assessment of WDN. This work proposes a novel approach to analyze IVS, which is based on the construction of the graph of segments and isolation valves generated by the IVS. The application of the recently proposed relevance-based (WDN-tailored) betweenness centrality to such graph is used to rank the importance of segments and isolation valves. Two WDNs of different sizes are used to demonstrate and discuss the strategy also from a practical perspective.

1. Introduction

Reliability of Water Distribution Networks (WDNs) is a classic issue. It refers to the system ability to provide an adequate service to consumers even in abnormal operating conditions (Xu & Goulter, 1999). Two general classes of reliability (mechanical and hydraulic) are defined based on failure event type (e.g., Farmani et al. (2005)). Mechanical reliability refers to the system abnormal working conditions due to its component failure (e.g., pipe breaks), while hydraulic reliability refers to the system abnormal working conditions due to its standard hydraulic boundary conditions failure (e.g., abnormal increase of the customer demand). Mechanical failures always involve valves shutdown to isolate the failed component, thus the isolation valve system (IVS) plays a relevant role.

In the last decades, mechanical reliability has been widely studied, but not accounting for the IVS.

Tung (1985) considered six techniques for analyzing WDN reliability, while Jacobs and Goulter (1988) and, later, Yang et al. (1996) introduced the graph theory and statistical metrics for reliability assessment of WDNs. Todini (2000) proposed the resilience index to quantify the WDN reliability, which was modified by Prasad and Park (2004) by accounting for the uniformity in diameter of pipes connected at each node as a surrogate measure of the redundancy of water paths in the system in case of mechanical failure. More recently, Creaco et al. (2016) extended Todini's resilience index to the pressure-driven analysis, while Liu, Savic, et al. (2017) proposed other surrogated measures to account for reliability in WDN design. In fact, the reported studies assume that it is possible to separate each single pipe of the system when failed by assuming the *N valve* rule (Walski et al., 2006), that is, the existence of two isolation valves at the ending nodes of each pipe, which is not realistic from a technical standpoint.

On the contrary, real WDNs are characterized by a much more parsimonious IVS and planned or unplanned works ask for valves shutdown, which usually isolate a network "segment" including many pipes and nodes. Such operation changes network topology, which is the domain of the WDN hydraulics (e.g., Alvisi et al., 2011; Giustolisi & Savic, 2010; Walski, 1993a, 1993b). Therefore, a consistent analysis of WDN mechanical reliability with respect to real technical needs must account for the actual IVS, and not only for the type of failure event (Giustolisi, 2020; Liu, Walski, et al., 2017; Walski et al., 2006).

Furthermore, in the context of mechanical reliability analysis, isolation valve is itself an element that can fail to close. In fact, each isolation valve works few times during its service life and, therefore, the system mechanical reliability can be lower than expected because the actual IVS functionality is uncertain, unless a maintenance program is carried out. Due to the high number of isolation valves, an effective maintenance program could be supported by identifying the most relevant isolation valves, that is, those that, in case of malfunctioning, would create the greatest impact on supplying water to users, thus reducing the mechanical reliability of the network.

Giustolisi (2020) addressed this topic in a comprehensive way, based on advanced hydraulic modeling of the actual demand supplied to customers during abnormal functioning conditions due to valves shutdown and the failure probability of each isolated segment. This work demonstrated that the reliability is determined by network connectivity (topology) and hydraulics, proving that the optimal IVS with respect to topology minimizes the overall "risk of disconnections" referred to segments. Nonetheless, it could be useful to account for the topological position of each segment within the "network of segments" generated by the IVS as well as the importance of each isolation valve. From this perspective, the relevance of each segment with respect to other technical/operational aspects like public uses (e.g., hospitals), the presence of water sources (tanks, reservoirs, pumping stations), etc., could be accounted for (Giustolisi et al., 2020).

In the present work, we propose the IVS analysis using the concepts of CNT to rank the importance of two elements: (a) the segments and (b) the isolation valves.

We propose a novel bipartite graph representing the IVS. It is composed by two sets of vertices representing the segments generated by the IVS and isolation valves. CNT betweenness centrality will be used to analyze the novel IVS bipartite graph to rank, separately, the importance of segments and isolation valves. The betweenness centrality increases the importance of segment and isolation valve vertices that are traversed many times by shortest paths connecting each couple of graph vertices. However, we here used the WDN tailored of the betweenness centrality recently proposed by Giustolisi et al. (2020). In this way, the intrinsic relevance of the vertices (e.g., the segment risk of disconnection) can be considered during the analysis, resulting in a global assessment of the IVS. Results provide information of practical relevance to drive maintenance programs of isolation valves and possibly an IVS retrain to improve WDN reliability.

The paper is organized as follows. Next section summarizes a background on the application of CNT to WDN analysis; then, the proposed methodology is described in detail, recalling the WDN-tailored centrality metrics here used for reliability analysis. The proposed strategy is exemplified on a small network (Apulian WDN), assuming a basic IVS, and applied on a larger real WDN (Real Apulian WDN) to demonstrate and discuss the novel aspects of the strategy, as well as some relevant technical issues.

2. Complex Network Theory Metrics for WDN Reliability Analysis

CNT analyses assume the paradigm that most of the existing systems in nature work as networks aiming at different scopes, such as studying the network connectivity and models (Barabási & Albert, 1999; Lämmer et al., 2006; Watts & Strogatz, 1998), performing division into modules/segments (clustering/partitioning; e.g., Newman & Girvan, 2004; Newman, 2006a, 2006b), assessing system vulnerability (Albert et al., 2004; Holme et al., 2002; Iyer et al., 2013), etc. In the last decade, further advanced theories, and approaches to the study of networks have been proposed by several researchers (e.g., Albert & Barabasi, 2002; Barabási, 2012; Newman, 2010).

A classic topic of the application of CNT to network analysis is to study their reliability/vulnerability considering random and intentional failures of vertices/links. CNT describes network reliability by analyzing the impact of such failures at nodes on the shortest paths between any couple of vertices in the network. The analysis of connectivity structures, based on the probability distribution of the number of links connected with each vertex of the network (nodal degree), allows a network classification ranging from *random* to *scale-free* affecting vulnerability features.

The *random* networks (Erdös & Rényi, 1959, 1960), where the nodal degree distribution is randomly distributed around an average value, are characterized by a high homogeneity. The Poisson model is often used to approximate their nodal degree distribution. The *random* networks show lower and more realistic values of nodal degree than *regular* networks, for which the shortest paths between two nodes are too large, since they are highly ordered (Milgram, 1967). The *small world* networks have a behavior between the *regular* and *random* networks (Watts & Strogatz, 1998), while the *scale-free* networks are characterized by nonhomogeneous nodal degree distributions, where many nodes have a low degree and few nodes (called hubs) have a high degree (Barabási & Albert, 1999).

Such classification of networks according their nodal degree distribution helps in assessing the vulnerability/reliability of real networked systems (Albert & Barabasi, 2002; Newman, 2003, 2010), for example, *regular*, *small world*, and *random* networks present a significant structural resistance to both random failures and intentional threats, while *scale-free* networks show a very high structural resistance to random failures but a weak resistance to intentional threats (Albert et al., 2000), for example, at hubs. Giustolisi et al. (2017) showed that the network connectivity structure of WDNs is random since the different role of nodes (vertices) of a water system is not considered in classic CNT.

The application of CNT to WDNs is a recently developed technical-scientific research field. It deals with connectivity analyses of networks to extract useful information to characterize the hydraulic system domain (e.g., Giustolisi et al., 2017; Yazdani & Jeffrey, 2012a), to cluster/segment the network (e.g., Giustolisi & Ridolfi, 2014; Hajebi et al., 2016; Perelman & Ostfeld, 2011), to assess vulnerability (e.g., Torres et al., 2016; Yazdani & Jeffrey, 2012b), etc.

Although the above-mentioned network classification can play a crucial role in assessing WDN reliability, network structure of WDNs is different from other networked systems studied in CNT, since WDNs are infrastructure networks like power systems (e.g., gas, electricity, etc.) and transportation systems (e.g., railways, roads, etc.). The infrastructure networks are constrained by (a) two-dimensional space and (b) spatial impediments (Barthélemy, 2011). This implies that the maximum nodal degree is generally very low (i.e., typically lower than seven); consequently, the nodal degree distribution spans in a very limited range, thus the resulting statistical inference based on nodal degree is unreliable.

Giustolisi et al. (2017) demonstrated that WDN are mainly *random* networks, using the *neighborhood nodal degree* (the sum of the nodal degrees of the nearest neighbors, i.e., the adjacent nodes), used to compute nodal probability. However, the same authors argued that the results were driven by the fact that the vertices of classic CNT all have the same role, while in WDN nodes (e.g., of tanks, of reservoirs, of demands, etc.), they have different roles, that is, relevance with respect to system functioning. Therefore, Giustolisi et al. (2019) modified some centrality metrics of CNT to account for WDN peculiarities. The authors proposed the WDN-tailored versions of the most suitable centrality metrics for spatial networks: betweenness, closeness, and degree (Freeman, 1977; Marchiori & Latora, 2000; Newman, 2010).

Giustolisi et al. (2020) developed the vertex intrinsic relevance-based degree, closeness, betweenness and edge betweenness metrics in order to embed the information about the intrinsic characteristics of vertices, and thus to account for relevance of each vertex. Since the metrics proposed by Giustolisi et al. (2020) couple information on intrinsic relevance of vertices and network topology, they can be used to rank the importance of segments and valves. Indeed, such metrics identify the most important elements of the IVS to support the maintenance planning of isolation valves, and possible actions to increase the reliability of the network through the retrain of the IVS.

3. Analysis of the IVS Using a Bipartite Graph and WDN-Tailored Betweenness Centrality

The IVS identifies network segments that are separated from each other by isolation valves. Here, we propose a two-step strategy as follows:

1. The definition of the bipartite graph for IVS, that is, a graph with two sets of vertices for segments and isolation valves
2. The analysis of the IVS bipartite graph using the WDN-Tailored Betweenness centrality by Giustolisi et al. (2020)

The WDN-tailored Betweenness centrality allows assigning the intrinsic relevance (Giustolisi et al., 2020) to each vertex of the bipartite graph composed by isolation valve-vertices and segment-vertices. In other words, it allows considering that each node of the bipartite graph has its intrinsic relevance due for example, to the risk of disconnection of the specific segment, while for the standard CNT metrices each vertices has the same (unit) relevance (Giustolisi et al., 2020).

Consequently, the analysis of the IVS bipartite graph by means of the WDN-tailored Betweenness centrality ranks the most traversed vertices (isolation valves or segments) considering the functional of the intrinsic relevance

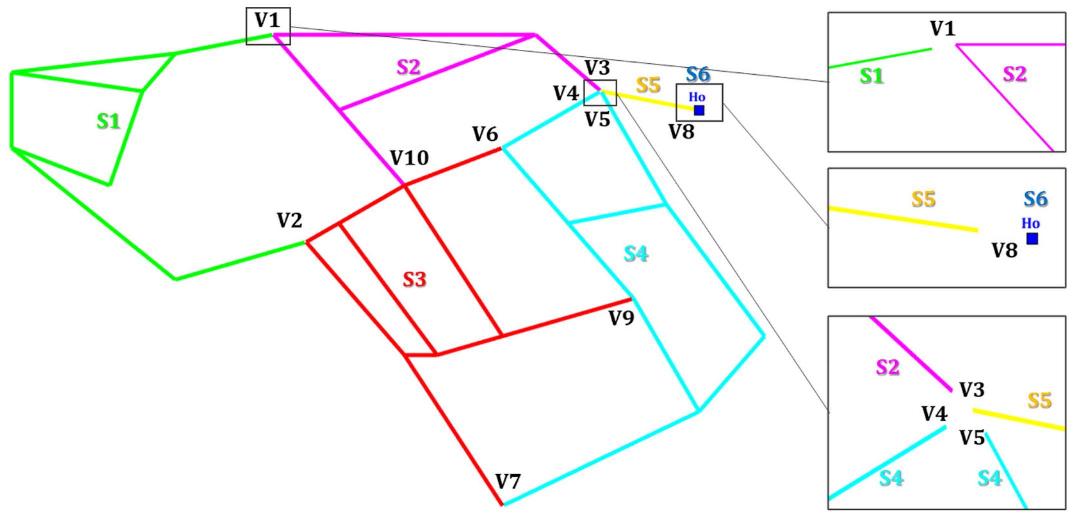

Figure 1. Segments generated by the isolation valve system in Apulian water distribution network.

of vertices, as will be reported later in the text. In fact, the shortest paths between each couple of vertices are weighted by the functional of the intrinsic relevance of the starting and ending vertices, for example, the risk of disconnection for segment vertices. Thus, the vertices of the bipartite graph representing isolation valves and segments result in being ranked as important by the specific CNT metric application.

From practical perspective, this information points out the segment whose disconnection is the most critical for network functioning and the valves that need to be prioritized for maintenance works since their malfunctioning would increase the impact on water supply in case of planned or emergency works.

3.1. IVS Bipartite Graph, That Is, Graph of the Segments and Isolation Valves

The IVS divides the network into segments which can be detached by closing isolation valves. Therefore, each isolation valve can be seen as a conceptual cut in the network and the IVS divides the network into components (i.e., segments). The segments can be composed of (a) multiple pipes and nodes; (b) a single node (e.g., a reservoir, a node separated by isolation valves at every pipe joining that node); (c) a single pipe (isolation valves at both ending nodes of the pipe). Each valve is useful to separate two segments, or it is not useful because it is internal to a segment. Figure 1 shows the segments identified in the Apulian WDN (Giustolisi & Savic, 2010) by its IVS. There are six segments identified by colors, one of which is composed by one node only (i.e., the reservoir H_0); the 10 valves (all useful) are drawn as gaps separating segments.

The IVS induces a bipartite graph where vertices are divided into two disjoint sets representing (a) the isolation valves and (b) the segments. For the sake of clarity, we refer to pipes/nodes about the WDN model, and to edges/vertices about the bipartite graph. Segments that include one or more pipes and two or more nodes of the WDN are designated here as pipe-segments. Segments made of only one node are designated as node-segment; this is the case of the reservoir in Figure 1 that is equipped with a valve separating it from the WDN.

Figure 2 shows the graph of segments generated by the IVS and the isolation valves. Segments are represented as yellow vertices (pipe-segments) or light green vertices (node-segment), drawn in the barycentric position of each segment, while valves are represented by red vertices. The edges of such graph (dotted lines) connect the first set (isolation valves) and second set (segments) of vertices. Each segment-vertex can relate to any number of isolation valve-vertices, while each isolation valve-vertex connects only two segment-vertices.

Figure 3 shows on the left the IVS graph of valves and segments generated by the IVS and, on the right, its conceptual representation as bipartite graph characterized by edges, whose number equals two times the number of isolation valves, and by vertices, whose number equals the number of segments and isolation valves.

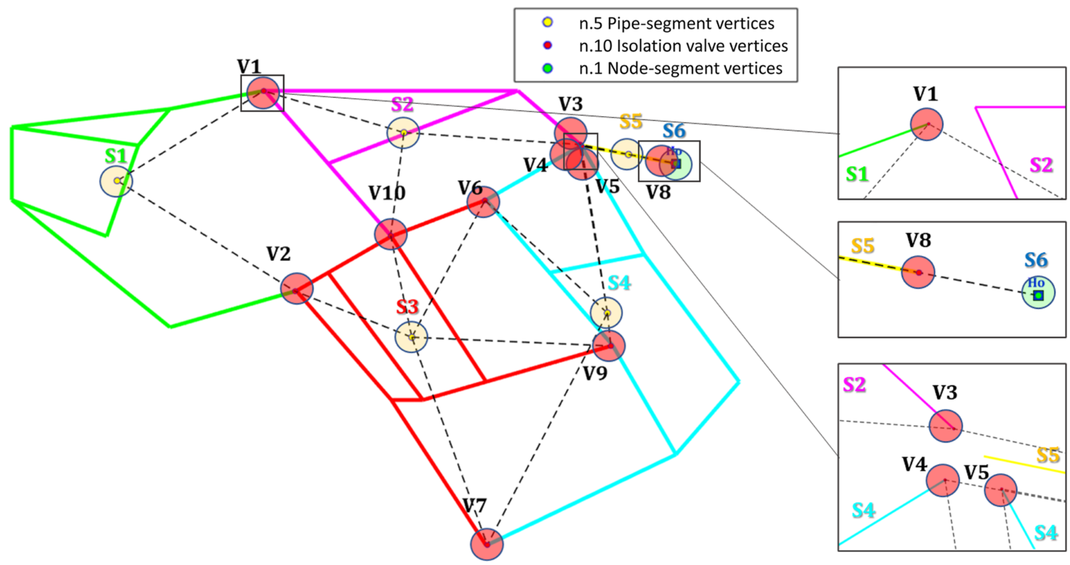

Figure 2. Generation of the graph of segments and isolation valves in Apulian water distribution network.

As mentioned above, the *N valve* rule IVS is not realistic for WDNs, although it is useful here to clarify the generation of the IVS graph. Figure 4 shows the Apulian WDN, assuming the *N valve* rule IVS, that is, two isolation valves are assumed at both ending nodes of each pipe. This means that the IVS define segments, whose number equals to the number of pipes (segments with only one pipe each) and nodes (segments with only one node each). Therefore, isolation valve-vertices in the graph connect pipe-segment vertices with node-segment vertices; as such isolation valve-vertices are double than the number of pipes, according to the *N valve* rule assumption. In this case, the layout of the graph degenerates in the original connectivity graph of the WDN (therefore colored pipes of the Apulian WDN coincides with dotted edges of the IVS graph in Figure 4).

3.2. IVS Bipartite Graph Analysis by WDN-Tailored Betweenness Centrality

We here use the WDN-tailored Betweenness centrality to rank the importance of the isolation valves and segments of the IVS bipartite graph. Therefore, the main idea is to apply the WDN-tailored Betweenness centrality, recently developed by Giustolisi et al. (2020), to the IVS bipartite graph, to extract information about the importance of segments and isolation valves. To this purpose, the feature of each segment (e.g., the risk of disconnection as in Giustolisi (2020)) and of each isolation valve (e.g., pipe importance) needs to be defined. Those features

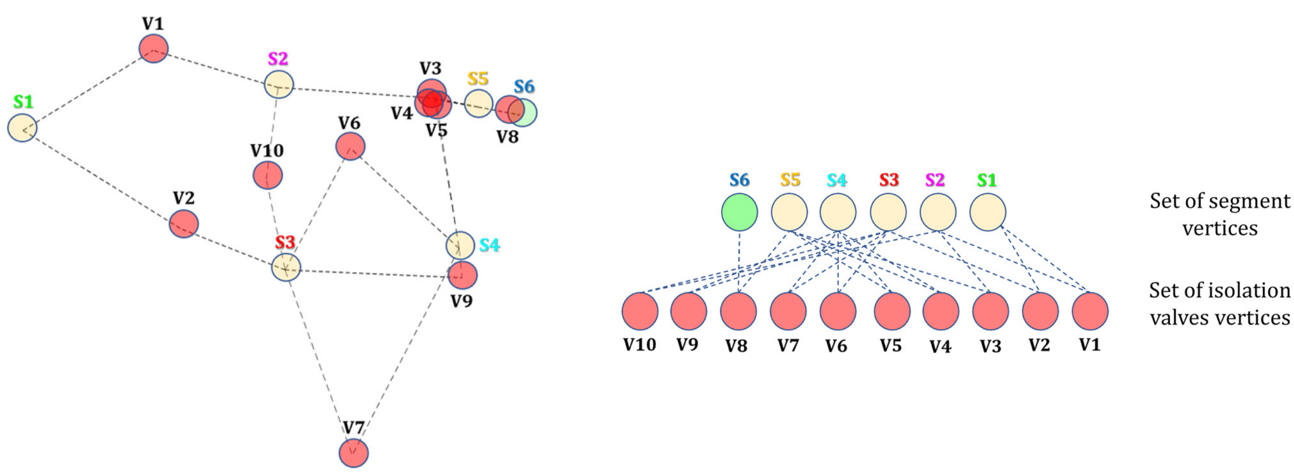

Figure 3. Bipartite graph of the isolation valve system in Apulian water distribution network.

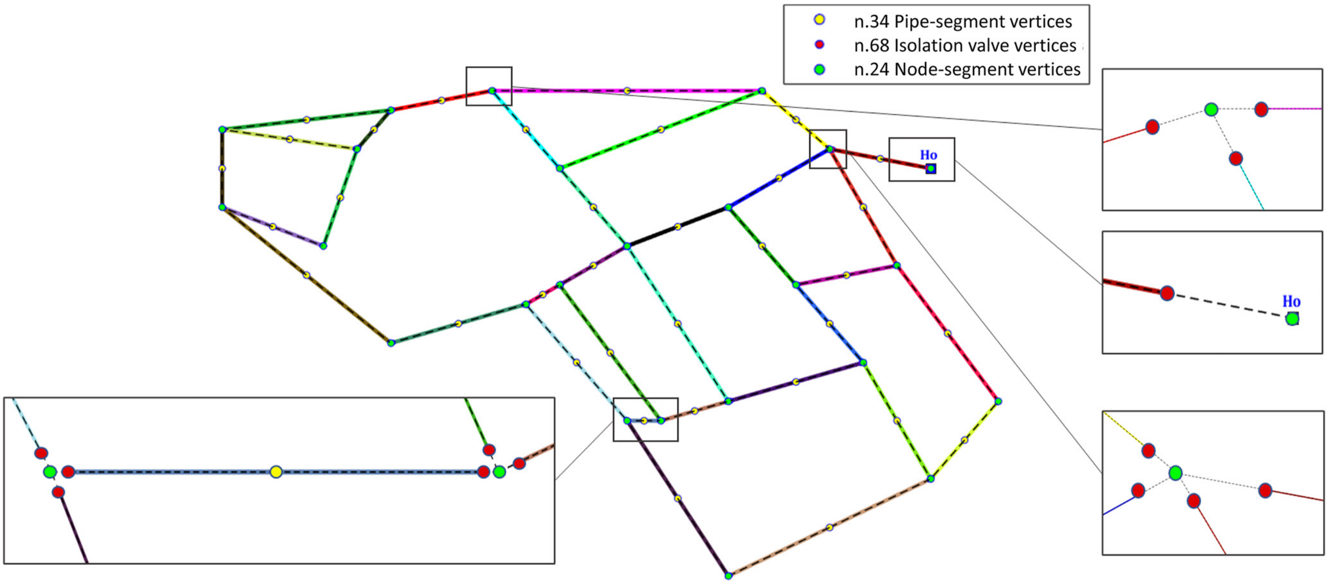

Figure 4. Generation of the graph of segments and valves in Apulian water distribution network assuming N valve isolation valve system.

become the intrinsic relevance of the vertices of the IVS bipartite graph, allowing to calculate the WDN-tailored Betweenness centrality.

The standard Betweenness metric is defined as follows:

$$B(v) = \sum_{s \neq v \neq t \in N} \frac{\sigma_{s,t}(v)}{\sigma_{s,t}} \tag{1}$$

where the Betweenness of a vertex v, $B(v)$, is based on the number of shortest paths $\sigma_{s,t}(v)$ traversing v between all couples of vertices s and t; N is the number of vertices and $\sigma_{s,t}$ accounts for the occurrence that more than one shortest path might exist between s and t.

Therefore, after the identification of all the shortest paths between all the couples s and t, the values of B for each vertex depend on the network connectivity structure, which determines the number of times they have been traversed by the shortest paths between couples of vertices.

Using the standard Betweenness to the IVS bipartite graph, both the segment and isolation valve vertices have no intrinsic relevance, that is, they the same unitary intrinsic relevance as reported in Giustolisi et al. (2020). Therefore, applying the standard Betweenness will not account for information about the features of valves and segments, which is important for the analysis of a IVS of a WDN to avoid a misleading analysis.

For example, a valve-vertex traversed by the shortest paths between segment-vertices with high risk of disconnection is more important, independently on the connectivity position. In other words, the intrinsic relevance of vertices provides further information beyond that referred to the network connectivity allowing to identify important isolation valve because of their topological position along the main paths between risk segments.

From the isolation valve-vertices perspective, the relevance of an isolation valve is related to the impact of its possible malfunctioning, which requires the isolation of the two contiguous segments it separates. For example, the malfunctioning of valve V1 in Figure 2 or 3 would require the isolation of segments S1 and S2 to carry on works. Therefore, if an isolation valve-vertex is traversed by shortest paths between segment-vertices at high risk of disconnection, its malfunctioning is likely to increase the impact of planned or emergency works on segments connected by that valve.

To capture the interplay between the topological position of segments and valves and their intrinsic relevance as real components of an infrastructure network, the betweenness formulation in Equation 1 can be slightly modified embedding the intrinsic relevance of vertices of the IVS bipartite graph (Giustolisi et al., 2020):

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

where the function $f(R_s, R_t)$ allows weighting the shortest paths between couples of vertices. Note that $f(R_s, R_t)$ is problem dependent and allows embedding the exogenous information in the standard betweenness metric.

Without impairing the generalization of the proposed analysis, the mean value of the intrinsic relevance of each couple of vertices s and t $(R_s + R_t)/2$, is used here for $f(R_s, R_t)$ because it was demonstrated to emphasize the role of the intrinsic relevance (Giustolisi et al., 2020).

Here, we assume for segment-vertices the intrinsic relevance measured by the risk of disconnection, which is the product of the probability of failure of each segment and the "damage" computed as the inability to supply the required customer demand. The pipes failure probability is here surrogated using the pipe length, as suggested by Giustolisi (2020).

The relevance R_s of each segment-vertices (originated by pipe-segments and node-segments, Giustolisi (2020)) will then be the risk of disconnection. Note that the risk of disconnection is null for a segment composed by a single node corresponding to a water source.

However, the procedure assigns the relevance R_s of the segments (node-segments) corresponding to water source(s) as the sum of the relevance of the vertices belonging to the portion of the network influenced by that source of water segment (Giustolisi et al., 2020).

The relevance R_s of isolation valve-vertices here is assumed null because the valve importance will be derived from the IVS bipartite graph analysis. In fact, the valve importance will depend on the paths traversing the isolation valve-vertices considering that each shortest paths between a couples of vertices s and t of the bipartite graph are characterized by functional of the intrinsic relevance $f(R_s, R_t) = (R_s + R_t)/2$.

Therefore, the valve or segment importance will depend on the summation of the relevance $(R_s + R_t)/2$ of the shortest paths between each couples s and t considering three occurrences:

1. $f(R_s, R_t) = (R_s + R_t)/2$ when the shortest path involves two segments-vertices
2. $f(R_s, R_t) = R_s/2$ or $R_t/2$ when the shortest path involves one segment-vertex and one valve-vertex
3. $f(R_s, R_t) = 0$ when the shortest path involves two valve-vertices

Consequently, the rankings of a segment or an isolation valve importance increases when it is traversed by shortest paths involving segment-vertices characterized by greater intrinsic relevance R.

Figures 5 and 6 show the methodology applied to the IVS in Figure 2. It allows ranking the importance of segments and isolation valves according to the values of metrics in Equation 2.

Consistent with the analysis of impact of possible interruptions, the segments including the reservoir (S6) and the trunk main feeding the network (S5) are the most relevant. Segment S1, has a lower relevance mainly due to its topological position, that is, it is traversed by a low number of shortest paths between two segments-vertices.

In Figure 6, the analysis ranks the isolation valve connecting the reservoir (V8) to the WDN as the most critical, consistent with Figure 5. The second highest relevance is for valve V3 consistent with the observation that, in case of malfunctioning of V3, segments S2 and S5 would be disconnected, preventing from supply of water to the WDN. From a technical perspective, this means that V8 and V3 have the highest priority of maintenance, as a proactive action to improve WDN reliability. It is also worth noting that valve V4 has relevance lower than 1% (white circle); this happens because segments S4 and S5 are already connected though V5 which has about 30% relevance. A similar condition happens for valves separating segments S3 and S4, where relevance is about 10% for V6 and lower than 1% for V7 and V9. This approach aims at reducing the number of valves that has priority for inspection/maintenance by pointing out only one isolation valve for each couple of segments.

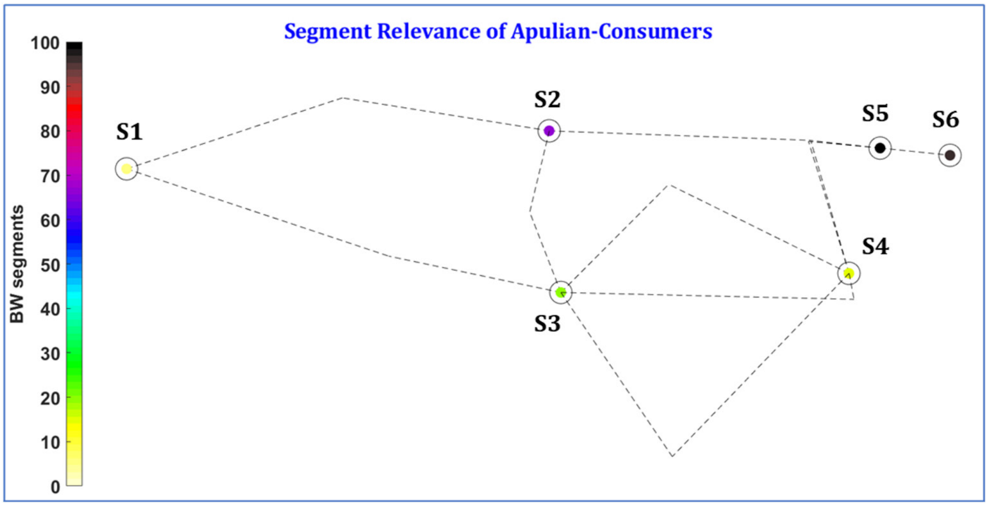

Figure 5. Ranking of relevance of segment in Apulian water distribution network.

4. Case Study: Real Apulian WDN

The proposed methodology is applied on a real WDN, whose model includes 1,814 pipes, 1,585 nodes, and 3 reservoirs. The IVS includes 1,055 isolation valves, eight of which are not useful to separate segments. Therefore, the bipartite IVS graph is composed of 843 segment-vertices (3 referring to water sources) and 1,047 valve-vertices. Thus, the bipartite graph is composed of 1,825 vertices and 2,094 edges.

Without impairing the generalization of the proposed analysis, the WDN-tailored betweenness (Giustolisi et al., 2020) is used considering the risk of disconnection for the intrinsic relevance of segment-vertices, while the intrinsic relevance of valve-vertices is assigned null. Consequently, the ranking of the importance of segments and isolation valves of the IVS is driven by the shortest paths between each couple of vertices, which is weighted according to the mean value of the intrinsic relevance of the starting and ending vertex of the path. Therefore, the analysis grasps the importance of segments and isolation valves of the WDN in relation to topology and segment risk of disconnection. Note that the shortest paths involving two isolation valve-vertices do not contribute to the analysis because $R_s = R_t = 0$.

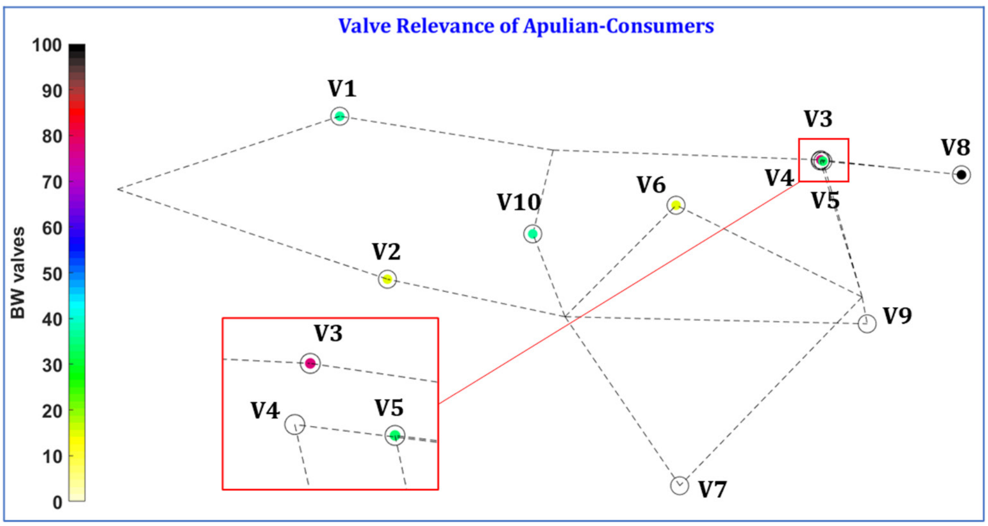

Figure 6. Ranking of relevance of isolation valves in Apulian water distribution network.

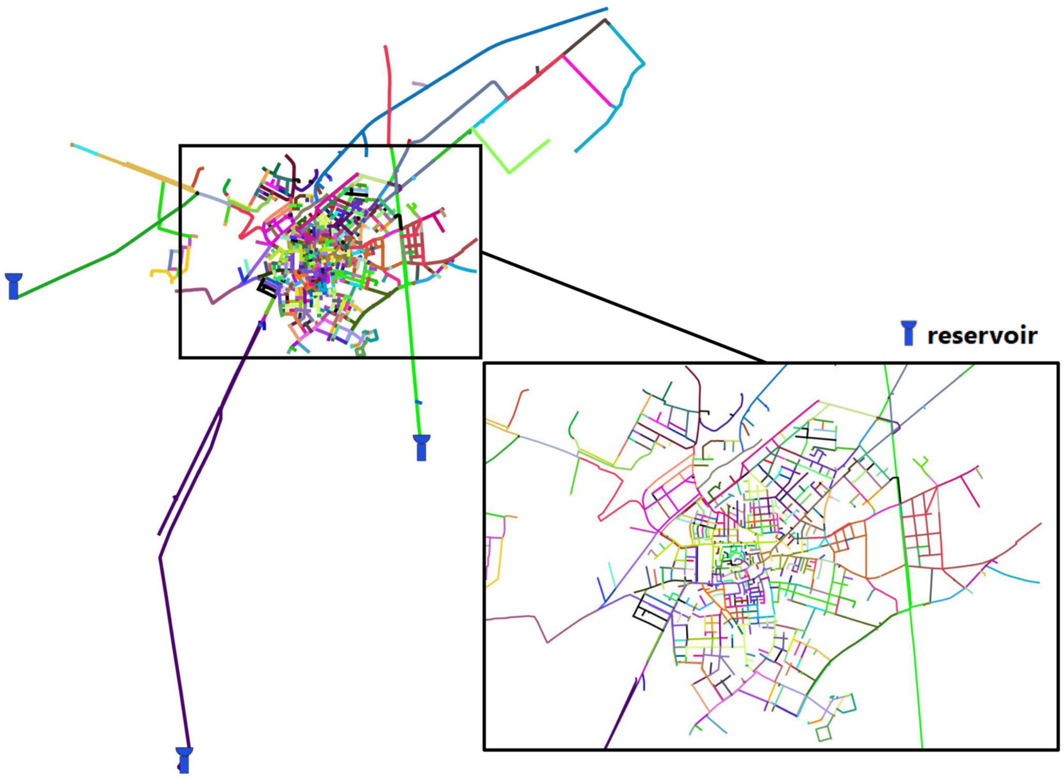

Figure 7. Segments generated by the Isolation Valve System in Real Apulian water distribution network.

Figure 7 shows the original WDN layout of the analyzed real WDN, which is characterized by three reservoirs. The figure shows the segments generated by the IVS of the analyzed real WDN, represented in different colors; as in the zoomed box, in its center, the network is characterized by a high-density IVS resulting in a huge number of segments highly interconnected each other.

Figure 8 shows that the IVS generates 65 nodes-segments, three of which are reservoirs. The zoomed box shows that some segments are linked with contiguous segments by many valves, resulting in a few hubs in the IVS graph topology.

Such evidence is confirmed by the ranking of segments relevance in Figure 9, which reports the results of the WDN-tailored Betweenness centrality analysis for the Real Apulian WDN. The figure shows in the global picture on the left the bipartite graph generated by the IVS of the network indicating the relevance of segments through the increasing dimensions of the segment-vertices (i.e., the yellow and green ones in Figure 8). It immediately emerges that the relevant segments are few if compared to the multitude of low-relevance segments, as clearly showed in the picture on the right, that focuses only on the most relevant segments. The zoomed box shows the central area of the network, where there are many small contiguous segments (as above observed in Figure 8) and where only a few segments are crucial (i.e., hubs).

The lower part of Figure 9 shows in a diagram the values of the WDN-tailored Betweenness centrality ordered from highest to lowest. The green-framed box focuses the attention on the few very relevant segments, $B(v) > 30$, shown in the picture at the top right, which in the case study are only 21.

It is worth noting that, differently from the Apulian WDN reported in previous section, in the Real Apulian WDN the relevance of node-segments representing the reservoirs is not maximum. This happens because there are multiple water sources, each providing only a portion of the supplied demand; consequently, the intrinsic relevance of vertices coinciding with each water source is lower than expected.

Therefore, information coming from such ranking provides a priority for proactive maintenance (e.g., planned replacements/rehabilitations, cleaning operations, relining, etc.) on segments ranked as the most relevant, as

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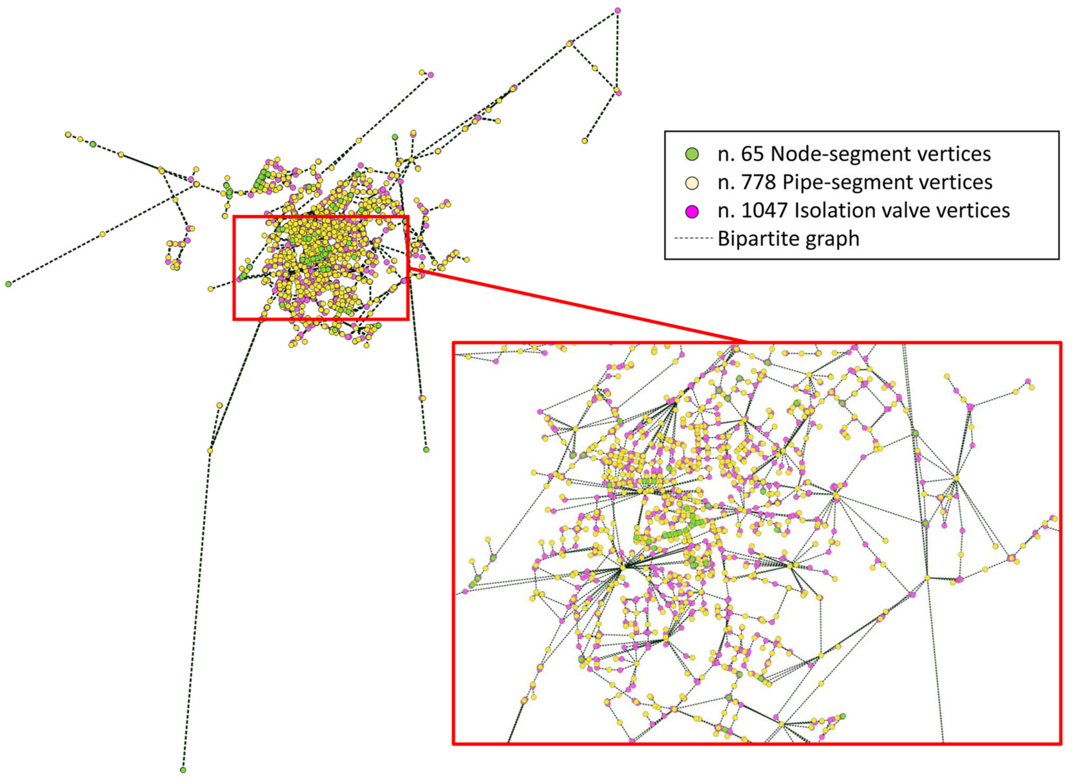

Figure 8. Bipartite graph of segments and isolation valves in the Real Apulian water distribution network.

well as support reactive maintenance (e.g., burst repairs), thus limiting the inconveniences (i.e., unsupplied demand, pressure deficit, etc.) associated with maintenance operations as much as possible. From WDN reliability perspective, this means that the interruption of few segments has a relevant potential impact in terms of unsupplied demand to consumers; vice versa, the interruption of many other segments is going to not have a relevant impact on water supply.

Consistent with the segment relevance analysis, the analysis of isolation valves relevance in Figure 10 shows that some valves are more relevant than others, especially those separating segments with the highest relevance. This emerges clearly when looking at the picture in the upper left of Figure 10, and even better in the picture in the upper right, which focuses on the few valves characterized by high relevance. The zoomed box shows more clearly where the isolation valves with greater relevance are placed, that is often in connection with segments with high relevance. The lower part of Figure 10 shows in a diagram the values of the Betweenness centrality for isolation valves, ordered from highest to lowest. The blue-framed box focuses the attention on the few very relevant segments, $B(v) > 30$, shown in the picture at the top right, which in the case study are only 20.

Therefore, this analysis, from the perspective of the isolation valves, provides a valid support to the utility in order to identify the most important valves of the IVS; this information can be useful during the IVS maintenance operations, identifying a priority for valve inspection and allowing the available budget to concentrate on the valves which, in case of failure, cause the greatest problems for customers. Similarly, in the proactive or reactive maintenance operations on the network, the knowledge of the most important valves allows the utility to better define the operational aspects of its interventions on the network (e.g., choosing the most appropriate timing of interventions, evaluating actions to mitigate the disservice, etc.) in order to decrease the impact on users resulting from the interventions.

As observed above for the segments and also in the case of isolation valves, it appears that those closest to the reservoirs (see the upper left picture in Figure 10) are certainly important according to the metric used, but they are not crucial, due to the existence of three sources and therefore the possibility that, in case of a valve failure, the network is still fed by the reservoirs that are still connected.

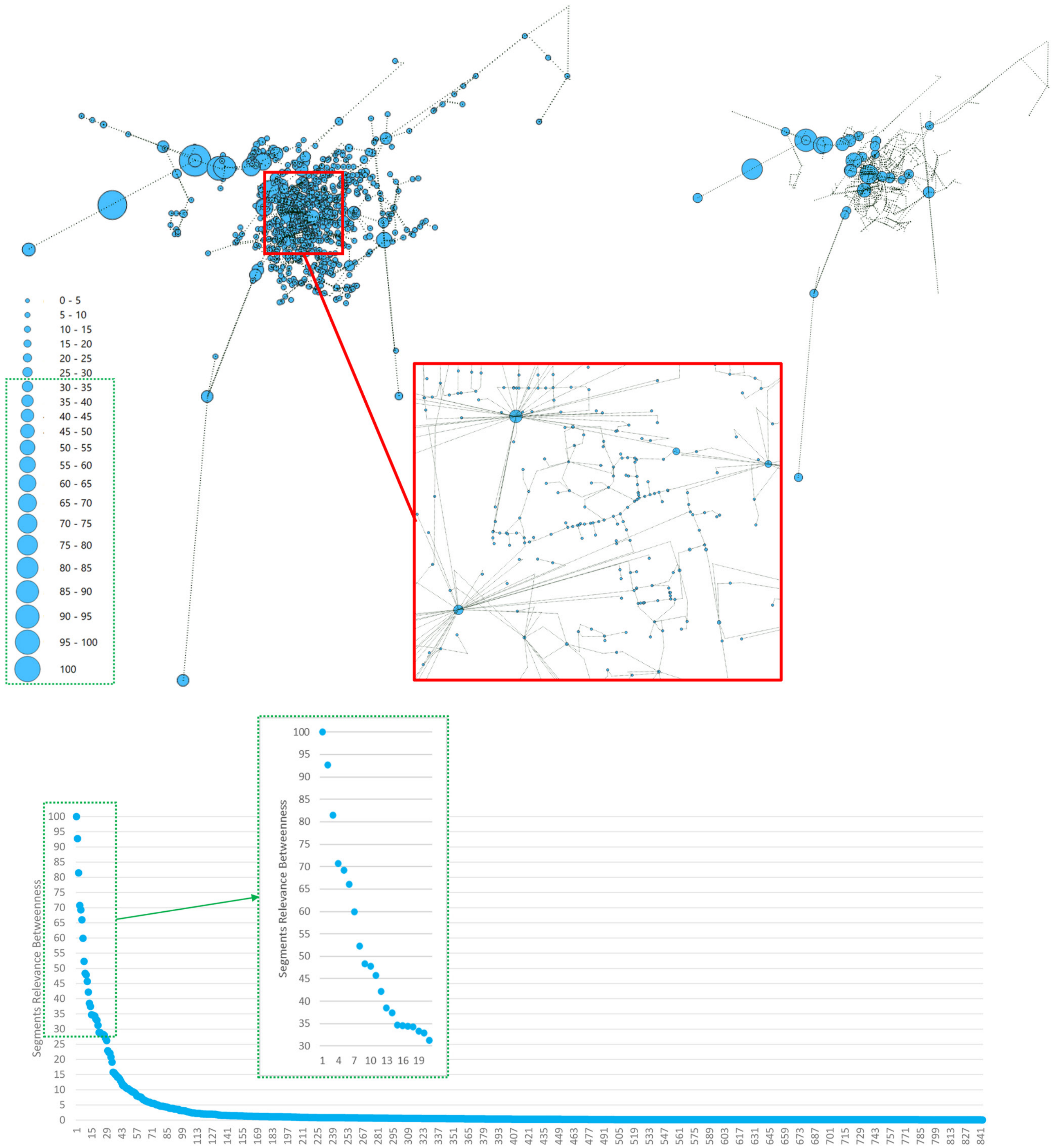

Figure 9. Ranking of relevance of segments in Real Apulian water distribution network.

Finally, it is worth noting that the results of this analysis, and therefore the ranking obtained for valves and segments of the analyzed network, strictly depends on the IVS currently existing. It is the result of the succession of construction and maintenance interventions carried out on the network in at least 100 years of management by the utility. For this reason, beyond generally heuristic economic criteria (e.g., containment of installation costs), the distribution of isolation valves has wide margins for economic and functional optimization, by means of valves retraining.

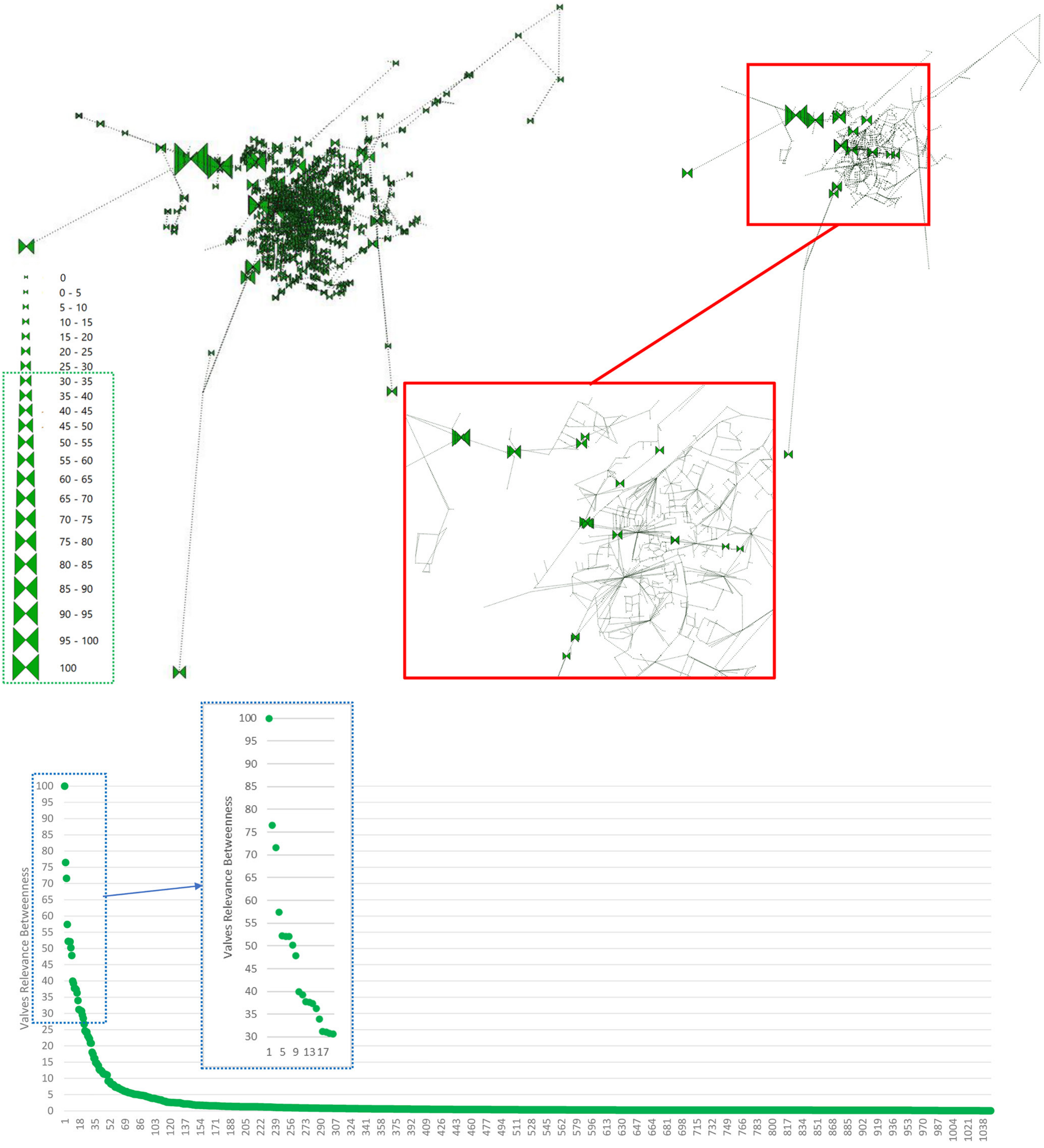

Figure 10. Ranking of relevance of isolation valves in Real Apulian water distribution network.

This suggests that possible future retraining of the IVS could use the WDN-tailored Betweenness centrality as an indicator to drive the optimization of isolation valves, pursuing a more uniform distribution of segment relevance to improve WDN reliability, that is, moving toward a *uniform* structure of the graph according to CNT.

5. Discussion and Conclusions

The proposed methodology provides a novel approach to point out those isolation valves and segments that are highly relevant for WDN mechanical reliability. It conjugates the topological information about the connectivity between segments and isolation valves, with the impact of segment interruptions, as represented by the water demand unsupplied to consumers.

The latter information is defined as relevance of vertices in the bipartite graph of segments and isolation valves, as generated by the real IVS, using the recently proposed betweenness centrality metrics by Giustolisi et al. (2020).

The analysis provides an explicit ranking of the most relevant segments, whose interruption should be avoided by carrying on regular inspections and proactive maintenance. The distribution of segment relevance also provides a methodology to support possible retraining of the IVS, aimed at maximizing the uniformity of segment relevance. The analysis of a real WDN shows that results are also consistent with the existence of multiple water sources, whose relevance corresponds only to a portion of the supplied water and the topology provides alternative paths traversing the segment and valve vertices.

Against the assumption of null relevance of the valves (i.e., Rs of isolation valve-vertices = 0), the analysis returns a ranking of the most important isolation valves in the network, thus providing a lineup for their inspections or maintenance.

In addition, the segments analysis suggests that all valves separating a segment should be assigned with the same priority; this means that the valves separating the most relevant segments gain a greater importance in defining the inspection/maintenance plans of the IVS.

It must be remarked that the proposed methodology does not involve any hydraulic modeling, but only exploits the information on network topology and water demand distribution through the network. As such, it can support the identification of the most impacting interruption scenarios considering the most relevant segments, when detailed hydraulic analyses cannot be performed. This approach would be especially useful in large WDNs to avoid computationally expensive simulations of interruptions in less relevant segments.

The present work is expected to open further directions of research. They may include the investigation on using other features as relevance of segments and valves to support WDN analyses from different perspectives; the reliability analysis accounting for the time-variance of demands over an operating cycle; the use of the bipartite graph to drive the optimal retraining of IVS; or the application of the same approach to support the analysis of district metering areas.

Data Availability Statement

Data on Real Apulian WDN are confidential in nature; the corresponding author can provide additional information upon request. The used software has not a significant impact on the findings and any code can be written to implement the procedure as described in the manuscript.

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