



# A Pipe Ranking Method for Water Distribution Network Resilience Assessment Based on Graph-Theory Metrics Aggregated Through Bayesian Belief Networks

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## Abstract

The resilience assessment is crucial for many infrastructures, including water supply and distribution networks. In particular, the identification of the ‘critical’ components (nodes or pipes) whose failure may negatively affect network performances and system resilience is a key issue, with a direct relevance for decision-makers involved in planning, management and improvement activities. Among the multiple methods and tools available, the use of graph-theory metrics is a cutting-edge research topic, as the analysis of topological properties may provide simple yet reliable information on the performance of complex networks. In the present work, we aim to overcome the limit associated to the use of individual graph-theory metrics, identifying a subset of relevant metrics that are directly connected to network resilience properties, using them to perform a ‘network degradation analysis’ in case of single pipe failure and finally proposing an aggregation of the results using a Bayesian Belief Network. Ultimately, the proposed methodology provides a ranking of the most critical pipes, i.e. those that contribute most to system resilience. A real water distribution network in Italy is used for model development and validation.

**Keywords** Drinking water supply · Resilience assessment · Graph Theory metrics · Bayesian Belief Networks · Pipe ranking

## 1 Introduction

Water Distribution Networks (WDNs) are critical assets, which are required to provide safe drinking water under a wide range of operational and management conditions, including failures (Herrera et al. 2016; Meng et al. 2018). WDNs are sensitive to failures and disturbances, which can adversely affect system operation (Shuang et al. 2019). An increasing attention is therefore being given—among the others—to the potential imbalance between supply and demand under extreme events, to ageing and to a potential increase in the vulnerability of WDN components (Shuang et al. 2019). Assessing system performance under

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multiple challenges is thus crucial for water utilities and, more in general, for decision-makers involved in the management of water supply and distribution services (Pagano et al. 2018a; Ghandehari et al. 2020).

The concept of resilience is emerging in the sector, typically defining the capacity of a system to resist, absorb, withstand and rapidly recover from external stresses and exceptional conditions (Diao et al. 2016; Butler et al. 2017). Specifically for WDNs, the hydraulic resilience measures the ability of a network to maintain supply under failure. As resilience level only manifests with disturbances, resilience-based approaches require that system performance be assessed in case of perturbation, even independent on the threat (Meng et al. 2018).

Multiple different approaches to WDN resilience assessment exist, which can be broadly classified as either performance-based or property-based (Yazdani and Jeffrey 2012; Pagano et al. 2019). The first class includes approaches which rely on the use of hydraulic models to analyze system performance under multiple failure scenarios (Mugume et al. 2015; Diao et al. 2016). The latter class of methods, instead, focuses on the link between inherent system properties—i.e. the topological characteristics—and system performance (Yazdani and Jeffrey 2012; Meng et al. 2018). Graph Theory (GT) provides a mathematical basis for analyzing key system properties which could affect its hydraulic operation (also in case of failure), under the consideration that ‘*the structure affects function*’ (Strogatz 2001) and that a strong connection with resilience exists (Butler et al. 2017; Shuang et al. 2019). Several authors recently debated the interconnections and trade-offs related to the use of both classes of methods for WDN resilience assessment, as well as specific limitations (Torres et al. 2016; Hwang and Lansey 2017; Pagano et al. 2019). In particular, property-based approaches may provide quick, practical and robust results without complex and detailed calculations, although the inclusion of non-topological characteristics (e.g. demand, pipe length and diameter) may definitely help better aligning the results with WDN properties and performances (Shuang et al. 2019; Simone et al. 2022).

Within this framework, the present work proposes a novel model based on use of multiple GT metrics to perform a ‘network degradation analysis’ (i.e. an assessment of network performances under component failure) in case of single pipe failure events, ultimately providing a simple ranking of pipe relevance for WDN resilience. The analysis considers pipe failures regardless of the causal threat, which makes the methodology suitable for the analysis of multiple hazards. The main element of innovation is the use of multiple GT metrics, whose relevance for WDN resilience analysis has been already proven, which helps overcoming the limited representativeness of individual metrics. The results are then aggregated with a BBN. Reference is made to a real WDN located in Italy.

The work is structured as follows. After the present Introduction, Sect. 2 provides a thorough background on the use of GT metrics to support WDN analysis and on the value added of using BBN for integration. Section 3 fully describes the methodology. Section 4 provides a description of the case study, while results are summarized in Sect. 5. Lastly, Sect. 6 includes a critical discussion of the results and some concluding remarks.

## 2 Background of the Work

### 2.1 Graph Theory Metrics for WDN Analysis

A WDN can be represented as a nearly planar mathematical graph (i.e. edges only intersect at nodes)  $G=(V, E)$ , where  $V$  (vertices) corresponds to  $n$  nodes and  $E$  (edges) corresponds

to  $m$  pipes. The peculiarity of WDNs is that every target node ( $T$ ) should have at least one path of edges connecting to a source node  $S$  (Herrera et al. 2016; Lorenz and Pelz 2020). GT approaches have been increasingly used in the WDNs analysis both to describe network-level properties and to identify important nodes and links (Porse and Lund 2016; Ponti et al. 2021). A specific target of such analyses is WDN resilience assessment, as metrics can be used to assess system performances under disruption (Lorenz and Pelz 2020).

Going further into details, several studies used the information provided by GT metrics to support optimization of WDNs, specifically in terms of resilience enhancement of large and complex networks (Sitzenfrei et al. 2020). In this direction, a few studies use GT with the aim of identifying a potential correlation between topological and operational parameters, which may provide information on network structure and resilience (Yazdani and Jeffrey 2011; Torres et al. 2016). Some studies aim specifically at assessing the importance of individual components in large infrastructure systems, using for example, centrality metrics (Porse and Lund 2016) and the betweenness centrality (Agathokleous et al. 2017). Meng et al. (2018) identified, based on a literature review, a set of attributes which represent key topological properties of WDNs. The authors highlighted that a strong correlation exists between certain metrics of resilience and topological attributes (connectivity, network efficiency and modularity).

Recently, GT-based approaches have been also widely used to describe the structural properties of water networks, with a specific focus on failures. Among the others, Yazdani and Jeffrey (2011) used network topology and connectivity to analyze system functionality following perturbations such as single or multiple component removal, due to either random or targeted failures, highlighting that the removal even of a small fraction of nodes/links may significantly affect network operation. Yazdani and Jeffrey (2012) used GT measures to analyze WDN vulnerability and robustness against failures, proposing an innovative hybrid metric which combines topological and physical information to define a pipe criticality rank. Yazdani et al. (2013) proposed a ‘multi-metric’ approach to network topology analysis to support primary evaluation of robustness or vulnerability against component failures. The Authors remarked that while each metric captures specific aspect(s) of network behavior and performances, no single metric can be considered exhaustive and a metric standardization process, along with an aggregate ranking is needed. Porse and Lund (2015, 2016) tested the relevance of GT approaches to support large-scale water infrastructure network assessment, focusing on potential system changes, and ultimately suggesting how to improve the capability of the system to be resilient to changing conditions. di Nardo et al. (2018) and Giudicianni et al. (2021) developed a procedure for WDN resilience assessment based on the use of fractal and topological metrics, and highlighting the relevance of the average path length to identify important paths and key pipes, whose failure may affect network resilience.

In terms of data requirements, the computation of GT metrics for WDN basically requires topological information, which allow describing the system as a graph based on an adjacency matrix (a mathematical description of how nodes are connected through edges). However, it should be mentioned that some of the GT measures can be computed in a ‘weighted’ form, i.e. attributing specific weights/information to nodes or edges (Yazdani and Jeffrey 2012; Meng et al. 2018). In such case, very basic information (e.g. pipe diameter and length) are needed. Several different weights have been proposed both in the form of pipe physical capacity (Yazdani and Jeffrey 2012) and in the form of surrogate measures of pipe flow resistance (Herrera et al. 2016; Pagano et al. 2019; Sitzenfrei et al. 2020).

In summary, the short review provided in the present section highlights that GT approaches may provide quick and practical results on WDN resilience under failure conditions. However, some limitations need to be highlighted, such as: i) the literature still lacks an explicit focus on the role of pipe network topology and a comprehensive analysis of how GT representations may characterize system performance (Torres et al. 2016); ii) several metrics might be of limited interest or capture only a small part of the behavior of the overall system; iii) no single GT metric can adequately capture the behavior of complex networks (Hwang and Lansey 2017; Meng et al. 2018; Pagano et al. 2018c; Balekelayi and Tesfamariam 2019).

## 2.2 Bayesian Belief Networks

BBNs are DAGs (i.e. Directed Acyclic Graphs) in which variables are connected through arrows, which define conditional dependencies whose strength is represented by conditional probabilities. BBNs therefore allow a probabilistic representation of interactions between variables, integrating a qualitative (graphical) and a quantitative (probabilistic) component. Full technical details on BBN building and use can be found e.g. in (Pearl 1988). BBNs are used, for the purpose of the present work, as a tool for aggregating the information provided by multiple GT metrics, following the approach implemented by (Balekelayi and Tesfamariam 2019).

Providing an overview of the manifold applications of BBNs is out of the scope of the present work. However, it is worth to highlight that several recent pieces of literature discussed in details the advantages and key features related to the use of BBNs in both environmental/water resources management problems and in risk analysis (Pagano et al. 2018a; Kabir and Papadopoulos 2019; Scricciu et al. 2021). Starting from these references, the relevance of using BBNs for the purposes of the present work, can be summarized as follows: i) BBNs can easily combine a large number of variables; ii) uncertainty is directly taken into account by means of the probability distribution of variables; iii) missing data in input variables can be handled; iv) expert and stakeholder knowledge can be quantitatively included into the modelling.

## 3 Description of the Approach

The proposed approach basically requires the computation of a set of topological metrics for WDN analysis (detailed in the Sect. 3.1), which are used to perform a network degradation analysis (Sect. 3.2), whose results are aggregated using a BBN (Sect. 3.3). The approach aims ultimately to define a pipe ranking which should reflect the relevance of individual pipes for WDN resilience.

### 3.1 Selection of GT Metrics

The review proposed in the Sect. 2.1 highlighted that a strong correlation between topological metrics and WDN resilience properties exists, corroborated also by the results of hydraulic models. In most cases, such correlation is based on individual GT metrics.

According to the scientific literature, three WDN properties can be well-described by topological indicators, namely: i) vulnerability to failures; ii) efficiency; iii) robustness. The strength of network connections is related to the WDN vulnerability to failures and, consequently, also to its resilience against efforts to isolate parts (Yazdani and Jeffrey 2012; di Nardo et al. 2018). Efficiency characterizes the information exchange (water flow for WDNs) in a network, under the assumption that information flows follows the shortest paths. Robustness represents the ability of the system to withstand perturbations while providing water to customers with an acceptable quantity and quality (Meng et al. 2018; Jung et al. 2019).

Following the evidence of the scientific literature, and based also on expert knowledge, we identified a set of relevant and non-redundant GT metrics, whose significance to describe the resilience of WDNs had been already proven in the scientific literature through hydraulic simulations, and that can be used to describe such properties. The list does not aim to be exhaustive, rather to provide a comprehensive overview of WDN properties. More specifically:

- The vulnerability to failures can be related to the *algebraic connectivity* (Torres et al. 2016; Meng et al. 2018) and to the *central point dominance* (Porse and Lund 2016).
- The efficiency can be related to the *average path length* (Yazdani et al. 2011; Porse and Lund 2016; Meng et al. 2018) and to the *network efficiency* (Balekelayi and Tesfamariam 2019).
- The robustness can be related to the redundancy and capacity of all possible routes from demand nodes (i.e. target nodes) to their supply sources, and is based on the analysis of the *shortest paths* (Herrera et al. 2016; Pagano et al. 2019).

The selected metrics are described further into details in the following.

The algebraic connectivity  $\lambda_2$  is the second smallest eigenvalue of the normalized Laplacian matrix of the network. It is widely used to describe network behavior against isolation of parts and fault tolerance. Although algebraic connectivity is strongly correlated with link density, it is more suitable to analyze network connectivity even for networks with the same number of nodes/links and a similar link density (Yazdani and Jeffrey 2011; Yazdani et al. 2011, 2013; Pagano et al. 2019). The comparison with hydraulic models highlighted a good correlation between time to strain/failure duration and algebraic connectivity (Meng et al. 2018).

The central point dominance  $C_b$  defines the average difference in node betweenness centrality of most central point  $C_{b,max}$  and all other  $n$  nodes  $C_{b,j}$ . It basically measures the concentration of the network topology around a central location, and ranges between 0 (regular or 'localized' network) and 1 ('centralized', e.g. star network) (Yazdani et al. 2011, 2013; Porse and Lund 2016). It is computed as follows:

$$C_b = \frac{1}{n-1} \sum_j (C_{b,max} - C_{b,j}) \quad (1)$$

From the physical point of view, scale-free networks (e.g. star-like topology with a very high centrality) are robust to random failures and a positive correlation exists between  $C_b$  and time to strain/failure duration, which suggests that a higher centrality tends to decrease the resilience of lattice networks like WDNs (Meng et al. 2018).

The average path length  $l_m$  is the average distance along the shortest paths between any two pairs of nodes  $d_{i,j}$ , compared to all possible pairs of network nodes (Yazdani et al. 2011, 2013; Yazdani and Jeffrey 2012; Porse and Lund 2016). It represents a good measure

of WDN efficiency, which is strongly affected by the existence of long-range connections between source nodes and target nodes (Meng et al. 2018). The average path length is computed as follows:

$$l_m = \frac{1}{n(n-1)} \cdot \sum_{i,j} d_{i,j} \tag{2}$$

Instead of the average path length, an index of network efficiency  $E[G]$  can be used, which defines the sum of all the reciprocals of path lengths between two nodes:

$$E[G] = \frac{1}{n(n-1)} \cdot \sum_{i,j} \frac{1}{d_{i,j}} \tag{3}$$

The use of  $E[G]$  helps avoiding mathematical issues that may arise in case of network disconnection, i.e. the distance between disconnected nodes becomes infinite (Porse and Lund 2016; Balekelayi and Tesfamariam 2019).

Several metrics might be used to analyze the network robustness, which expresses the ability of the system to withstand perturbations due to node/link removal. For the purposes of the present work, the contribution of each link to system robustness is estimated considering whether its failure/removal causes a disconnection between sources  $S$  and targets  $T$  or an increase of the shortest path(s) between them. The shortest paths connecting demand nodes to source nodes are computed in a weighted form, considering a simple hydraulic surrogate of flow resistance (reference is made to the Darcy-Weisbach formula as in Herrera et al. 2016; Pagano et al. 2019; Sitzenfrei et al. 2020). Basically, the head loss in each pipe  $k$  is calculated as follows:

$$h_{k,L} = A_k \cdot Q_k^2 \tag{4}$$

where:

$$A_k = \frac{0.0252}{0.3048} \cdot f(\epsilon_k, DN_k, Q_k) \cdot \frac{L_k}{DN_k^5} \tag{5}$$

In which  $\epsilon_k$  is the Darcy-Weisbach roughness coefficient,  $DN_k$ ,  $L_k$  and  $Q_k$  respectively the diameter, the length and the flow rate for the pipe  $k$ . The friction factor could be calculated, under specific assumptions, without a detailed information on the flow regime in the system, as demonstrated by (Sitzenfrei et al. 2020).

### 3.2 Network Degradation Analysis

Although the analysis of WDN topology already provides useful insights on network behavior, additional information related to network resilience with respect to random failures can be obtained through the network degradation analysis, which is based on the selective removal of either nodes or links (Porse and Lund 2016). In this work, instead of selecting specific components to remove, a systematic assessment of the effect of single edge removal is proposed. The network degradation analysis therefore ultimately suggests the importance of specific elements, through the analysis of the impact of their removal on network connectivity (Porse and Lund 2016; Pagano et al. 2019).

With specific reference to the metrics mentioned in the Sect. 3.1, the network degradation analysis basically requires the comparison between the value of each metric

in case of WDN ordinary operation (denoted in the following with the subscript 0) and under single pipe  $i$  failure (denoted in the following with the subscript  $i,f$ ). In order to make results directly comparable, a normalization is performed with respect to value obtained in ordinary operation, and the absolute value is considered. The metrics identified in the Sect. 3.1 are therefore computed as follows:

- Variation of the algebraic connectivity  $\Delta\lambda_2$ .

$$\Delta\lambda_2 = \left| (\lambda_{2i,f} - \lambda_{20}) / \lambda_{20} \right| \tag{6}$$

The algebraic connectivity  $\lambda_{2i,f}$  becomes 0 in case the removal of the edge  $i$  produces a disconnection of the network (i.e. two separate sub-networks are obtained). In such case the  $\Delta\lambda_2$  becomes 1.

- Variation of the central point dominance  $\Delta C_b$

$$\Delta C_b = \left| (C_{bi,f} - C_{b0}) / C_{b0} \right| \tag{7}$$

The variation of the central point dominance describes the effect of the removal of the edge  $i$  in terms of network connectivity (i.e. tendency to form a more centralized or localized network).

- Variation of the average path length

$$\Delta l_m = \left| (l_{mi,f} - l_{m0}) / l_{m0} \right| \tag{8}$$

The variation (typically an increase) of the average path length defines the effect of edge removal on network efficiency, highlighting specifically the increase of average geodesic distance between all couples of nodes.

- Variation of the network global efficiency  $E_g$ , which is usually defined as Topological Information Centrality ( $TIC$ ) and calculated as follows:

$$TIC = E[G]_0 - E[G]_{i,f} / E[G]_0 \tag{9}$$

The  $TIC$  provides an information on the importance of the failed components on the efficiency of the WDN.

- Variation of the Source-Target shortest path distance, which can either increase because of pipe failure or produce a disconnection between  $S$  and  $T$  nodes. Two metrics are specifically considered for the purpose (Pagano et al. 2019), namely: i)  $DD_j$  which defines the total nodal demand that becomes disconnected from all sources once edge  $j$  is removed; ii)  $SPC_j$ , which cumulates the shortest path change between all  $S$  and  $T$  nodes once the edge  $j$  is removed. A weight  $w$  is assigned to each source node  $S$ , representing the fraction of the total water inflow that is (on average) provided by the node.

A Matlab<sup>®</sup> code has been developed for the purpose of the present work, which uses also some of the Matlab Tools for Network Analysis (available at the following website [http://strategic.mit.edu/downloads.php?page=matlab\\_networks](http://strategic.mit.edu/downloads.php?page=matlab_networks)).

### 3.3 Aggregation of Results Using a BBN

As already mentioned, a BBN is used in the present work with the purpose of aggregating the information provided by the set of GT metrics used for WDN degradation analysis, ultimately providing a pipe ranking. The structure of the BBN comprises three levels: 1) input variables (i.e. the variation of the selected GT metrics obtained through the degradation analysis); 2) WDN resilience properties (i.e. vulnerability to failures, efficiency, robustness); 3) individual pipe contribution to WDN resilience. In other words, given the variation of the selected GT metrics in the WDN degradation analysis and the influence of such metrics on well-known WDN resilience properties, the influence of single pipe failure on WDN resilience is estimated. A probability distribution is given as output for the states ‘High’, ‘Average’ and ‘Low’. Pipes having a ‘High’ expected influence on pipe resilience should be prioritized in any planning, management and/or maintenance operation. An overview of the structure of the BBN model is provided in Fig. 1 (please consider that the Figure aims at providing information on the general structure of the BBN and therefore a uniform probability distribution is assigned to the input variables for the sake of simplicity).

The definition of input variables for the BBN requires that the relative (numerical) change of the selected metrics in the degradation analysis (as detailed in Sect. 3.2) is translated into linguistic values (e.g. ‘High’, ‘Average’, ‘Low’, ‘Null’). The classes have been defined by the analysts based on expert knowledge (Balekelayi and Tesfamariam 2019), considering the range and the distribution of the values of each variable (which should be changed in different applications of the model). The use of such classes helps simplifying the number of variables’ states and ultimately the model structure. The Conditional Probability Tables (CPTs) describe numerically the conditional dependence between the state of the *parent nodes* and the state of the *child nodes*, and allow quantifying the causal relationships in the causal chain. The BBN model was built using the Netica<sup>™</sup> software.

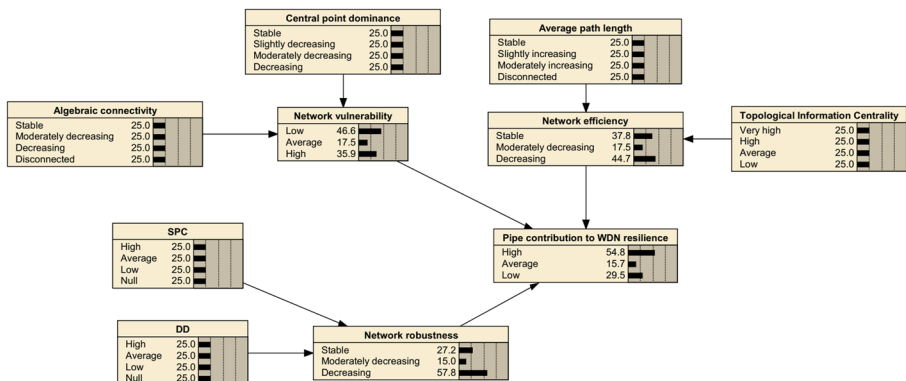


Fig. 1 BBN aggregating GT metrics for assessing the individual pipe contribution to WDN resilience



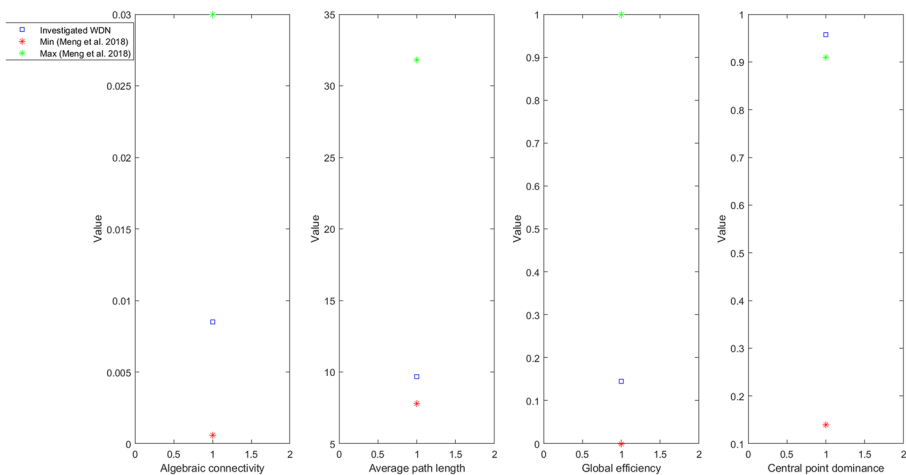
## 4 Short Overview of the Case Study

The methodological approach described in the present work has been developed with the support of an Italian Water Utility, whose WDN has been used for model development and testing. The water utility is located in the Central-Northern Italy and provides water to approximately 1 M users. The WDN basically comprises two main interconnected supply systems, fed by 7 source nodes, and has an overall length of approximately 400 km. Both iron (mainly upstream) and cast-iron (mainly downstream) pipes are used, with diameters ranging between 100 and 1400 mm. For the purpose of the present work, no specific hydraulic models and information are considered, and a topological representation of the WDN (Figure A1 in the Annex 1), with basic pipe characteristics is used only. No further details are included, as sensitive information on infrastructure characteristics and location need to be preserved.

## 5 Results

A basic characterization of the WDN under investigation has been performed considering some of the metrics described in the Sect. 3.1 and integrating the data by Meng et al. (2018). In the cited work, the Authors provided a range of values of such metrics (the extreme values are identified as *Min* and *Max* in the following Fig. 2) obtained from the analysis of 80 virtual WDNs. This is useful to compare the structure of the WDN under investigation with other networks.

While the value of all metrics falls between the *Min* and *Max*, the value of  $C_b$  is slightly higher than the *Max* value, suggesting that the network can be considered as significantly ‘centralized’ and that a node (edge) is located on many short paths. Following Yazdani and Jeffrey (2011), star-shaped topologies with central hubs are in general more economic and may facilitate transportation in the network, but show typically lower robustness due to the high sensitivity to the failure of the most central points.

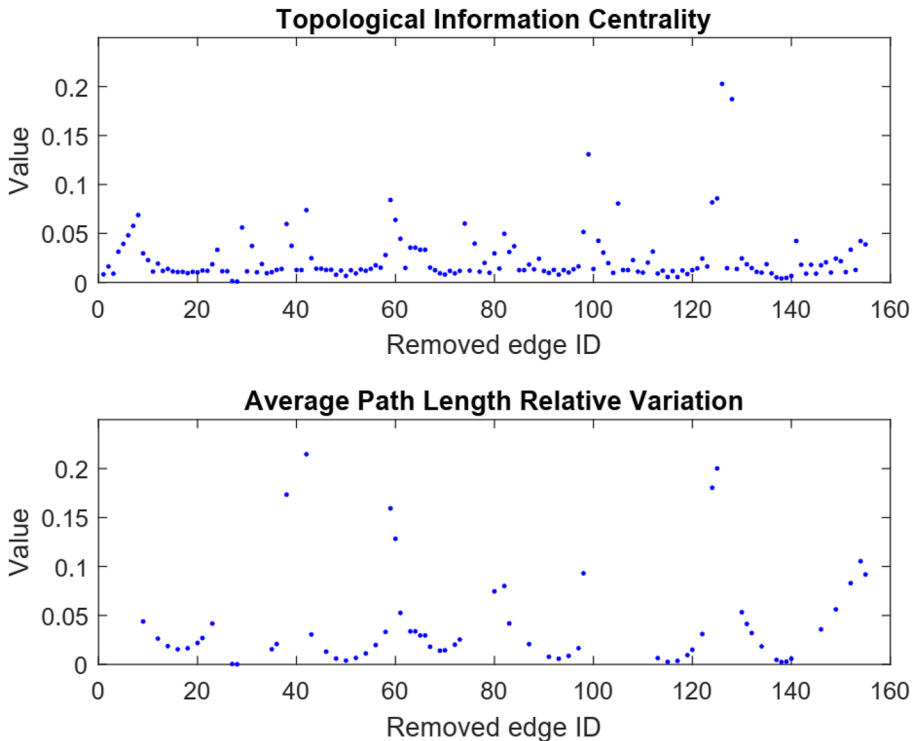


**Fig. 2** Comparison (over a set of metrics) between the investigated WDN and the values provided by Meng et al. (2018)

The core of the proposed methodology is the network degradation analysis, which is based on the characterization of the impact of individual pipe removal on the metrics identified in the Sect. 3.1. An example of the result, related to the two metrics contributing to Network efficiency (i.e. TIC and Average path length variation), is proposed in the following Fig. 3.

The change in the selected set of GT metrics (reference is made to the weighted form of the metrics) is fully detailed in the Table A1, along with the linguistic values that have been attributed by the analysts (as detailed in Sect. 3.3). More specifically the Table A1 includes, for each pipe of the network (table rows), the expected change in the values of the selected metrics in case of pipe failure. The linguistic values are associated according to the following criteria:

- Variation of the algebraic connectivity  $\Delta\lambda_2$ :
  - $\Delta\lambda_2 = 1$  ‘Disconnected’.
  - $0.3 \leq \Delta\lambda_2 < 1$  ‘Decreasing’.
  - $0.1 \leq \Delta\lambda_2 < 0.3$  ‘Moderately\_decreasing’.
  - $0 \leq \Delta\lambda_2 < 0.1$  ‘Stable’.
- Variation of the central point dominance  $\Delta C_b$ , normalized with respect to the maximum value:



**Fig. 3** Example of results produced by the network degradation analysis: variation in the value of specific metrics as a consequence of the failure of the pipes on the x-axis

- $\Delta C_b / \Delta C_{bmax} \leq 0.15$  'Stable'.
- $0.15 < \Delta C_b / \Delta C_{bmax} \leq 0.5$  'Slightly\_Decreasing'.
- $0.5 < \Delta C_b / \Delta C_{bmax} \leq 0.8$  'Moderately\_Decreasing'.
- $\Delta C_b / \Delta C_{bmax} > 0.8$  'Decreasing'.
- Variation of the average path length  $\Delta l_m$ 
  - $\Delta l_m \leq 0.05$  'Stable'.
  - $0.05 < \Delta l_m \leq 0.25$  'Slightly\_Increasing'.
  - $\Delta l_m > 0.25$  'Increasing'.
  - $\Delta l_m = Inf$  'Disconnected'.
- Topological Information Centrality (*TIC*), normalized with respect to the maximum value:
  - $TIC / TIC_{max} \leq 0.15$  'Low'.
  - $0.15 < TIC / TIC_{max} \leq 0.5$  'Average'.
  - $0.5 < TIC / TIC_{max} \leq 0.9$  'High'.
  - $TIC / TIC_{max} > 0.9$  'Very\_High'.
- Shortest Path Change (*SPC*)
  - $SPC = 0$  'Null'.
  - $0 < SPC \leq 15$  'Low'.
  - $15 < SPC \leq 100$  'High'.
  - $SPC > 100$  'Very\_High'.
- Disconnected Demand (*DD*)
  - $DD = 0$  'Null'.
  - $0 < DD \leq 5$  'Low'.
  - $5 < DD \leq 20$  'Average'.
  - $DD > 20$  'High'.

As described in the Sect. 3.3, the above classes have been defined by the analysts based on expert knowledge and with specific reference to the case study, considering the range and the distribution of the values obtained. The values should therefore not be interpreted as fixed. However the definition of the classes only aims at facilitating the transfer of results into the BBN model.

The BBN development then requires that the CPTs relating all variables are defined. The process of CPT definition has been performed in two steps: i) relating the state of the input variables to the resilience properties (i.e. vulnerability to failures, efficiency, robustness); ii) relating the state of the resilience properties to the level of system resilience. The CPTs have been defined by the analysts based on expert knowledge, but BBN are flexible enough to allow updates or changes in the CPTs as new knowledge is available. An example of CPT is included in the following Table 1.

Basically, the information from the degradation analysis provided in the Table A1 for each pipe of the network is used as input for the BBN run, which is performed using the 'Process cases' function.

Full results provided by the BBN model are included in the Table A2 (in the Annex). It includes, for each pipe of the network (rows), the probabilistic value associated to the three states ('High', 'Average' and 'Low' probability) associated to the main output variable, i.e. the 'Pipe contribution to WDN resilience'. From the practical point of view, specific attention is given to the value of the 'High' probability, as this should help identifying the pipes whose failure has the highest impact on network performance. A pipe ranking is performed accordingly.

**Table 1** An example of CPT relating the state of two parent nodes ('Algebraic connectivity' and 'Central point dominance') with the state of the child node ('Network vulnerability')

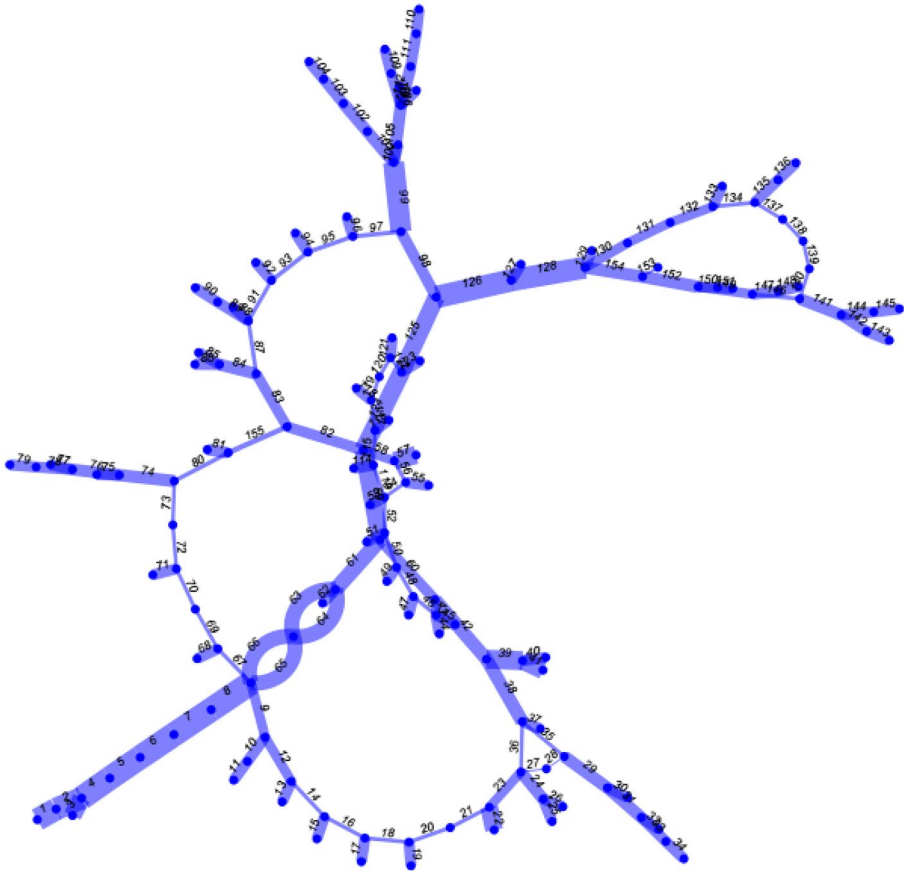
Algebraic connectivity	Central Point Dominance	Low	Average	High
Stable	Stable	100	0	0
Stable	Slightly decreasing	90	5	5
Stable	Moderately decreasing	85	10	5
Stable	Decreasing	80	10	10
Moderately decreasing	Stable	85	10	5
Moderately decreasing	Slightly decreasing	70	20	10
Moderately decreasing	Moderately decreasing	60	30	10
Moderately decreasing	Decreasing	40	40	20
Decreasing	Stable	30	50	20
Decreasing	Slightly decreasing	30	30	40
Decreasing	Moderately decreasing	25	25	50
Decreasing	Decreasing	20	20	60
Disconnected	Stable	15	15	70
Disconnected	Slightly decreasing	10	10	80
Disconnected	Moderately decreasing	5	5	90
Disconnected	Decreasing	0	0	100

A graphical summary of the results is provided in the following Fig. 4. The thickness of the lines is directly proportional to the value of the 'High-probability' of 'Pipe contribution to WDN resilience' which, according to the proposed methodology, identifies critical pipes for WDN resilience.

The results have been discussed with technicians of the Water Utility and validated based on their knowledge on network features and main criticalities, as no specific models are currently available for analyzing system resilience in full details and for modelling the impact of individual pipe failure on network performance. The value added related of a straightforward methodology capable to provide an overview of network resilience and to support identifying the most relevant pipes has been stressed. It has been also confirmed that the results provide a fair basic assessment and reasonable prioritization of network elements, although a more detailed validation should be performed also considering other networks, which could provide a wider basis of configurations and conditions.

## 6 Discussion and Concluding Remarks

The present work aims to develop a simple yet quantitative and robust approach to WDN resilience analysis in case of pipe failure events, based on the analysis of the impact of individual pipe failures on multiple network topological properties. A network degradation analysis is performed for the purpose and the results are aggregated through a BBN. The approach is promising and particularly suitable for data scarce environments and for supporting a straightforward pipe ranking without relying on complex hydraulic models. Furthermore, although the relevance of GT metrics has been already proven in the scientific



**Fig. 4** Graphical representation of the results for the case study. The line thickness reflects the value of 'High-probability' of 'Pipe contribution to WDN resilience'

literature, the aggregation of results performed through BBNs may help overcoming one of the main limits of the approach, i.e. the limited representativeness of single metrics and the need for integrating multiple information.

The core of the proposed methodology is the network degradation analysis, i.e. an assessment of the impact of component failure, which ultimately provides information of the relevance of individual pipes on WDN performance. The methodology has been developed and implemented on a real network in Italy, and the results discussed with the Water Utility, which provided a positive feedback on the adopted approach, highlighting the positive trade-off between the simplicity of the methodology and the quality of the results. The present work provides a proof-of-concept of the proposed approach, which is should be replicated on other networks.

However, some remarks on the methodology should be performed.

First of all, it is worth highlighting that the selected set of GT metrics is not meant to be neither exhaustive nor exclusive. The present work uses a limited subset of metrics, which provide diverse information on infrastructural topology, but whose connection with hydraulic behavior has been already proven in other studies. Other metrics have

been therefore neglected, as their inclusion may provide a limited value added to the methodology. Just to make an example, the ‘link density’ measures network connectivity and is strongly correlated to WDN resilience, particularly to the time to strain (Meng et al. 2018). However, it is not taken into account since it shows a very low sensitivity to single pipe failure, particularly for complex networks, therefore being almost useless for the purpose of the network degradation analysis.

Second, the main advantage of the proposed methodology is that no hydraulic models and no heavy computations are required to provide, through the degradation analysis, a basic identification of the most critical pipes for network resilience. However, the use of a ‘weighted’ form of the metrics helps explicitly taking into account some relevant properties of the system (e.g. diameter, roughness, etc.) and therefore better represent some physical characteristics of the flow conditions.

Third, the methodology has been developed with the aim to provide decision-makers (mainly Water Utilities and emergency managers) with a straightforward tool capable to support the immediate identification of the most critical pipes for network operation, i.e. those that contribute most to network resilience, based on the analysis of the impacts of single pipe failure on topology. The analysis is focused on pipe failures and therefore is independent on the threat, which makes the methodology usable for analyzing the impacts of multiple hazards. However, the methodology can be also used to analyze the effects of resilience-enhancing actions performed on the infrastructural systems (e.g. adding new pipes or modifying interconnections). This could provide relevant information, mainly useful at the strategic and planning level, to preliminarily assess and compare the effectiveness of multiple strategies for network improvement. In this direction, one of the most interesting future evolutions of the model could be related to the development of targeted scenario analyses, depending also on the analysis of relevant hazard and their characteristics which can help taking into account, for example, also the impacts of climate change (see e.g. Xiong et al. 2019).

Lastly, although the results of the methodology are promising, also according to the feedback received by one of the potential final users, the validation and calibration through additional networks would be worth. Particularly, this could allow also expanding the model so it can take into account more complex topologies, different hydraulic behaviors and even multiple pipe failure conditions. In this regard, one of the key features of BBNs, i.e. the algorithms support to learning from data, can be used both to optimize the structure of the model and to modify the CPTs. Synthetic networks and benchmarks could be used to run hydraulic simulations that can be used for this purpose.

Among the other prospective future developments of the model, we also see a relevant potential in the use of GT metrics for the assessment of the impact of water quality issues, as well as the extension to the model use to the phases of maintenance, rehabilitation, and replacement or inspection.

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## Declarations

**Ethical Approval** Not applicable.

**Consent to Participate** Not applicable.

**Consent to Publish** The authors have approved manuscript submission.

**Conflicts of Interest** The authors declare no conflict of interest.

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