Vulnerability Analysis of Water Distribution Networks Using Betweenness Centrality and Information Entropy

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Abstract

In recent years, many researchers have analysed the vulnerability of Water Distribution Networks (WDNs) from the hydraulic perspective. However, few works in literature have addressed the vulnerability problem from the topological point of view. This work adopts the information entropy to evaluate the topological vulnerability of a WDN from the character of its heterogeneity. The proposed method is based on the principle that a network with uniformly distributed centrality values exhibits a lower drop in performance in the case of partial failure of its components and therefore is less vulnerable. In order to demonstrate the proposed method, the paper presents two case studies, a real-world WDN of an Australian town and a network from the literature. Comparative analysis confirmed that a network with more homogeneous distribution of the nodal betweennes centrality values is less vulnerable against the random failure of its components than that of the one with heterogeneous distribution of these values.

Keywords

Betweenness centrality, Information entropy, Vulnerability analysis, Water distribution networks.

1. Introduction

Water Distribution Networks (WDNs) incorporate multiple interconnected interacting components, in which failure of any these components may lead to the system failure. The reliability of these networks are therefore major concerns for the water sector researchers and practitioners in ensuring public health, safety and societal welfare. The complexity of WDNs along with the extensive societal dependence on these networks emphasize the importance of studying and managing vulnerabilities (Johansson *et al*., 2013).

Vulnerability analysis of WDNs has been an active area of past research. Shuang *et al*. (2014) evaluated the nodal vulnerability of WDNs under cascading failure by monitoring pressure in nodes and flows in pipes during the cascading process. Fragiadakis and Christodoulou (2014) and Fragiadakis *et al*. (2016) performed a seismic hydraulic vulnerability assessment of urban water networks using survival analysis. Shuang *et al*. (2015) suggested different recovery strategies of WDNs, focusing on the vulnerability of nodes due to exceeding their hydraulic (pressure) capacity. Laucelli and Giustolisi (2015) evaluated the vulnerability of WDNs under seismic actions using a hydraulic modelling paradigm taking into account unsupplied demand to customers.

Such studies approach the vulnerability analysis of WDNs from a hydraulic perspective, which is concerned with satisfying flow and pressure requirements taking into consideration failures due to demand variation, undersized pipes, storage capacity, insufficient pressure, or combination of these conditions (Zhuang *et al*., 2013). However, due to the complex interactions among large number of subsystems and components, the exclusive hydraulic analysis of WDNs just partially describes the network performance (Gunawan *et al*., 2017). In the light of this, the topological vulnerability analysis, as a complementary approach, provides a robust model, thereby more accurate assessment of WDNs (Yazdani *et al*., 2011).

There is a small body of literature, which analyzes the vulnerability of WDNs from the topological point of view. The topological vulnerability analysis refers to analyzing the configuration of the network based on the graph theory techniques (Di Nardo and Di Natale, 2011). Perelman and Ostfeld (2011) constructed a topological connectivity matrix aimed at clustering the nodes in WDNs based on their connectivity, thereafter identifying weakly and strongly connected clusters. Yazdani and Jeffrey (2011 & 2012) examined the vulnerability of WDNs to the failure of individual components by identifying the critical components using metrics from graph theory. Sheng *et al.*, (2013) adopted a complex network-based model for exploring malfunction of WDNs by measuring the spectral properties and subsequently identifying the isolated communities.

The topological approaches discussed above assess the vulnerability of WDNs by adopting very generic topological properties of the network within which mainly the vulnerability problem at the local level is addressed. While vulnerability analysis of networks at specific location is of great importance for identifying the critical components, studies on how to quantify the topological vulnerability of a WDN as a whole remain scant. This work extends the earlier approach, proposed by the authors (Zarghami *et al*., 2018), to measuring the heterogeneity of the network using Shannon (information) entropy for assessing the global vulnerability of WDNs. In doing so, we adopt a graph theory quantity known as the betweenness centrality in order to establish a new vulnerability index. By situating our research in the entropy theory context, the potential of using the information entropy as a means to measure the homogeneity and heterogeneity of the centrality values is explored. Accordingly, we demonstrate how heterogeneity and homogeneity of the betweenness centrality values measured by the information entropy can be interpreted in terms of the network vulnerability.

The rest of the paper is structured according to the following plan. Section 2 recalls the notion of the betweenness centrality. Section 3 develops the proposed method and details the procedural steps to evaluate the vulnerability of WDNs. In Section 4, we present two case studies, a real-world WDN of an Australian town and a network from the literature, as illustrations of the proposed method. We draw conclusions in Section 4, followed by discussion of the avenues for future research.

2. Betweenness centrality

The centrality of elements in a network is concerned with identification of the elements with more central role than others (Qi *et al*., 2012). In recent years, a number of centrality measures have been devised to evaluate the importance of nodes and links in a network, within which different dimensions of the intuitive notion of the centrality are addressed (Brandes *et al*., 1999). For an overview the reader is referred to Boldi and Vigna (2013) and the references therein.

In this work, we identify the centrality of a network by adopting the betweenness centrality, which is the most widely used centrality measure. Betweenness centrality sets the basis for development of many other mathematically related measures (Lozares *et al*., 2015). Let us briefly recall some basic facts about this centrality measure.

Betweenness centrality is based on the idea that a given node is central if it lies between many other nodes (Cadini *et al*., 2009). Betweenness centrality of node i, $C_B(i)$, is defined as the number of shortest paths between pairs of nodes that pass through a given node and can be stated by the followings formula:

$$C_B(i) = \frac{1}{(n-1)(n-2)} \sum_{s \neq r \neq v} \frac{n_{s,r}(i)}{n_{s,r}} \qquad (1)$$

where n is the number of nodes in the network, $n_{s,r}(i)$ denotes the number of shortest paths between s and r passing through i and $n_{s,r}$ represents the number of shortest paths between s and r. $C_B(i)$ takes on values between 0 and 1 and attain its maximum value when node i falls on all shortest paths between two nodes.

According to Monge and Contractor (2003), betweenness measures the extent to which a node is directly connected only to those other nodes that are not directly connected to each other. It is in fact a measure of the degree to which a node serves as a bridge. Betweenness centrality is a medial centrality measure that accounts for the relationship between a node to pair of nodes rather than the relationship between a node to node (Bell, 2014).

Betweenness centrality successfully evaluates the impact of each node on the network performance and provides a numerical indicator to identify the network's most influential components (Lawyer, 2015). However, stand-alone use of this metric yields insufficient information as to the weaknesses of a network. An attempt is made in the following section to provide a solution to this problem by proposing an entropy-based vulnerability index.

3. Vulnerability analysis

In this section, the expected level of the network vulnerability is evaluated by computing the Shannon entropy of the betweenness centrality values.

Shannon entropy, introduced by Shannon (1948), is a widely used evaluated measure of choice, uncertainty and heterogeneity of a set of probabilities, which can be expressed by the following equation:

$$H = -\sum_{i=1}^{n} p_i \log_b p_i \tag{2}$$

where H is the entropy of distribution, p_i is the probability associated with the *i*th outcome, n denotes the number of possible outcomes, and b is an arbitrary logarithm base indicating the unit of entropy. For example, for *b=2*, *b=e* and *b=10*, the unit of entropy is respectively defined as bit, Napier, and decibels.

Shannon introduced Eq. (2) for complete probability distributions, where $\sum_{i=1}^{n} p_i = 1$, whereas Rėnyi (1961) developed a new definition, in which $0 < \sum_{i=1}^{n} p_i \leq 1$. In this work, we follow the definition proposed by Shannon, hence the normalized form of each betweenness centrality value is used by scaling it to the [0, 1] interval.

Let $C_B(i)$ be the betweenness centrality of node *i*, the normalized betweenness centrality is defined as the ratio of the betweenness centrality value to the sum of all betweenness centrality values, as such $\sum_{i=1}^{n_d} C_B(i) = 1$. The normalized centrality of node *i*, $PC_B(i)$, can be stated as follows:

$$PC_B(i) = \frac{C_B(i)}{\sum_{i=1}^{n_d} C_B(i)} \tag{3}$$

As can be seen from Eq. (3), the values of all betweenness centralities are first summed over each node, and are then scaled relative to the sum of all betweennes centrality values. Therefore, PC_B provides a numerical indicator to evaluate the relative contribution of a node to the all-pairs shortest paths in a network.

By substituting $PC_B(i)$, Eq. (2) can be restated as follows:

$$H_C = -\sum_{i=1}^{n_d} PC_B(i) \log_2 PC_B(i) \tag{4}$$

where H_{CD} is the entropy of the set of centrality values. For continuity, we set $0 \log_2 0 = 0$.

Intuitively, failure of a junction node with a high betweenness centrality value results in disruption of the service for many nodes in the network due to its central location. Therefore, in the case where all junction nodes are of equal value of the betweenness centrality, the debilitating effect on the network performance due to the failure of each individual node will be minimum. More precisely, the betweenness centrality values are conditionally reliant on each other. That is, if a high number of shortest paths passes through a particular node, then the likelihood of participation of the other nodes in the shortest paths decreases. This intuitive description is very reminiscent of the principle of Shannon entropy, which is a decreasing function of scattering of random variables, and attains its maximum value when all the outcomes are equally likely (Maszczyk and Duch, 2008).

In a network with n_d junction nodes, when all betweenness centrality values are equally likely, H_C is maximum when $PC_B = \frac{1}{n_d}$, thus:

$$H_{C,max} = -\log_2 n_d \tag{5}$$

The vulnerability index, VI, can be constructed based on the fractional differences between H_C and maximum achievable H_C. Thus, VI is defined as one minus the relative entropy as follows:

$$VI = 1 - \frac{H_C}{H_{C,max}} \tag{6}$$

The vulnerability index of the network falls within the range of [0,1], where a higher value of VI indicates the higher vulnerability, whereas a lower value implies the lower vulnerability. VI represents the comparative heterogeneity of the betweenness centrality values defined by H_C with respect to the maximum possible entropy value where all values are uniformly distributed (Singh, 2013). VI attains its minimum value ($VI = 0$), when $\{PC_B(i) \mid i = 1,2,\ldots,m\}$ is uniformly distributed . Theoretically, this case corresponds to the situation when all components in the network are equally central.

VI describes how severe the consequences of a random failure may be. It refers to the likely magnitude of a failure. That is, in the case when the nodes in the system are almost equally central, the severity of the random failure of a node is lesser than that of the case when some nodes are highly central and others are peripherals. In other words, when a very few central nodes dominate the network, the failure of each of these nodes leaves a large number of the households without water supply, which implies the severity of the failure and consequently a high vulnerability of the network.

4. Application

This section presents two case studies to illustrate the proposed vulnerability analysis of WDNs. An open-source graph analysis software, igraph (Csardi and Nepusz, 2006) is used to compute the betweenness centrality values (C_B) for each network. The vulnerability index of each network is then calculated by using Eq. (6). After computing the vulnerability index, we compare the vulnerability of two case studies.

4.1. Case study 1

The first case study is a real world WDN of Price, a small town in South Australia, located 140 km west of Adelaide, Australia. The network is a tree-shaped WDN, represented by 18 nodes connecting 17 pipes (Fig. 1). The layout for this case study has been obtained from the official website of South Australia Water company (http://sawater.maps.arcgis.com).

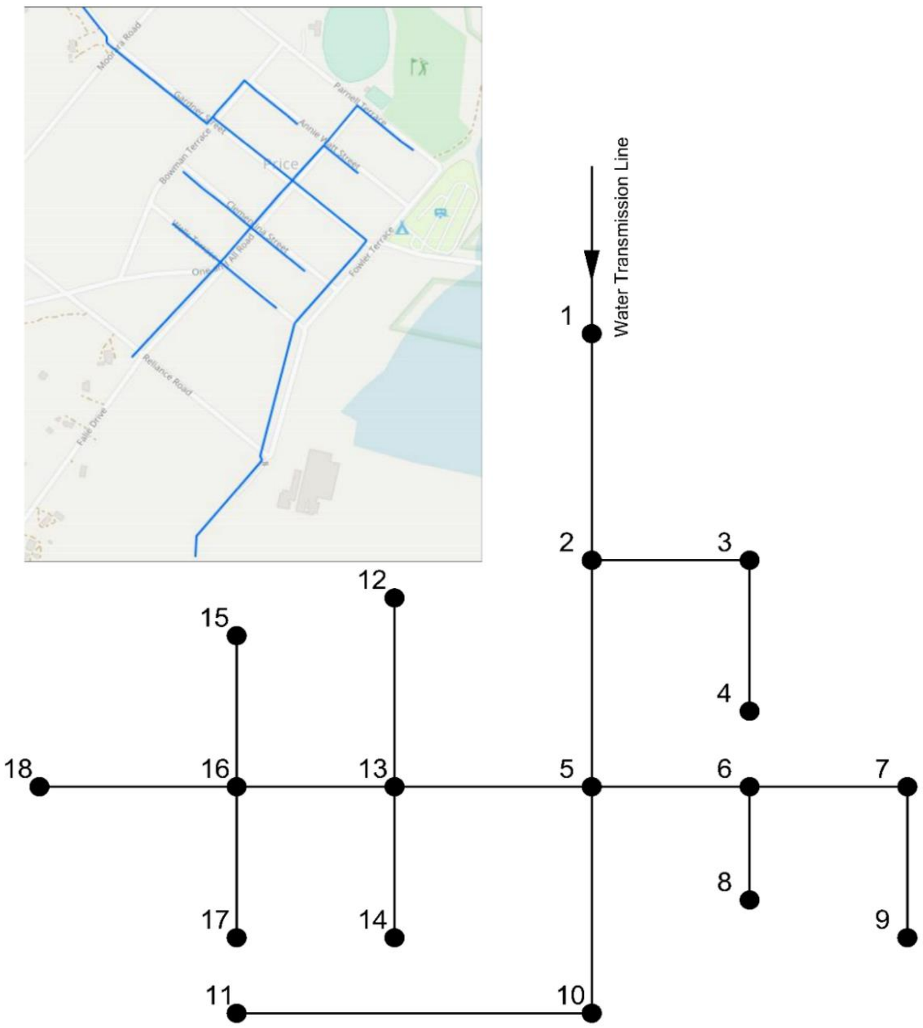

Fig. 1. Case study 1: Price water distribution network

We first obtain the values of betweenness centrality for all nodes, using igraph software. These values are then normalized, using Eq. (3). The betweenness centralities along with the normalized values are presented in Table 1.

Table 1. Betweenness centralities for the first case study

Node	C_B	PC_B	Node	C_B	PC_B
1	0	0	10	0.0110	0.0332
2	0.0588	0.1777	11	0	0
3	0.0074	0.0224	12	0	0
4	0	0	13	0.0662	0.2000
5	0.0956	0.2889	14	0	0
6	0.0331	0.1000	15	0	0
7	0.0147	0.0342	16	0.0441	0.1333
8	0	0	17	0	0
9	0	0	18	0	0

In order to provide a better visualization of the results in Table 1, the normalized betweenness centrality values are plotted in Fig. 2.

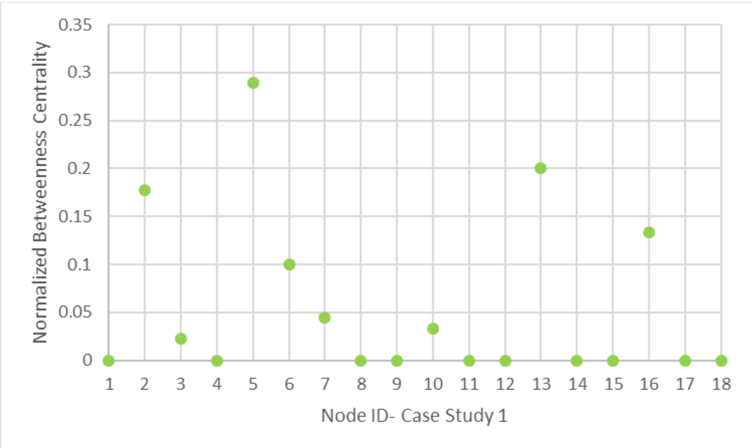

Fig. 2. Normalized betweenness centralities of nodes- case study 1

As noted earlier, PC_B measures a betweenness centrality importance score. As reported by Table 1 and Fig. 2, node *5* is scored *0.2889* and all other nodes have lower scores ranging downwards toward zero. This is because node *5* is centrally located in the network, thus when compared to the other nodes, it participates in a higher number of shortest paths between any given pair of nodes. As expected, nodes *4,8,9,11,12,14,15,17* and *18* take on the betweenness centrality value of zero, indicating that these variables play no role in any shortest paths.

It is now possible to calculate the vulnerability index described in section 3. Using Eq. (4), the entropy of the normalized betweenness centrality value obtained from Table 1 is $H_C = 2.6301$. Given $n_d = 18$, using Eq. (5), $H_{C,max} = -log_2 18 = 4.1699$. By substituting the results into Eq. (6), we obtain $VI = 0.3693$. The high value of VI describes how significant the likely consequences of failure may be. This can be interpreted as the evidence that due to the heterogeneous distribution of the nodal centralities in this case study, failure of a highly central node (e.g., node 5) leads to a significant loss of the performance in the network.

4.2. Case study 2

The second case study, as shown in Fig. 3, is a looped WDN taken from the literature (Islam *et al.*, 2014; Shuang *et al.*, 2014). As a means to illustrate the proposed vulnerability index, the case study is mapped into an undirected graph with a node set of size 27 and an edge set of size 40. Water is supplied from two reservoirs connected to nodes *1* and *3*.

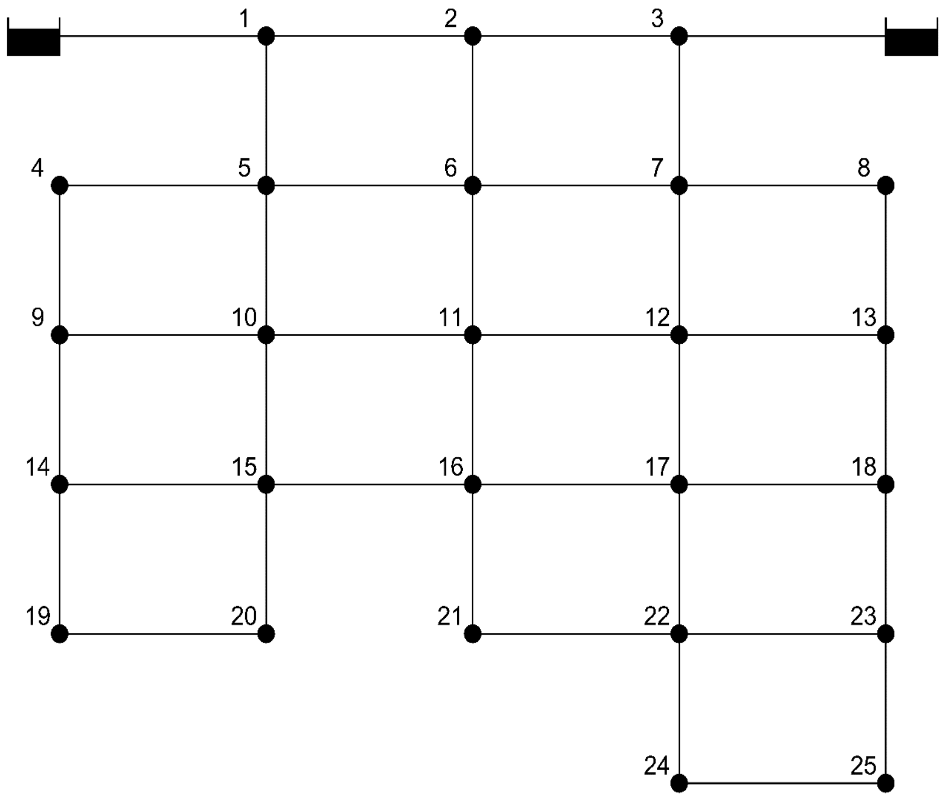

Fig. 3. Case study 2: An example WDN from the literature

Applying the same procedure as the previous case study, the parameters for obtaining the vulnerability index are listed in Table 2.

Additionally, we present Fig. 4 in order to provide a better visualization of the results without distracting the reader with numbers.

As shown in Fig. 4, the nodes in the second case study can be broadly grouped as follows. The nodes with $PC_B > 0.05$ and the ones with $PC_B < 0.04$. It can be perceived that the nodes in the former group are more central with considerable influences within a network by virtue of their central location; whereas the nodes in the latter group are more peripheral, lying on the smaller number of all-pairs shortest paths in the network. This observation is in consistent with the fact reported in Barrat *et al*. (2004), indicating that central nodes participate in highest number of shortest paths in the network than those of the peripheral nodes.

The similar calculations can be performed to obtain the vulnerability index for this case study as follows:

Eq. (4) $\rightarrow H_C = 4.2192$

$n_d = 25 \rightarrow H_{C,max} = -log_2 25 = 4.6439$

$(H_C = 4.2192, H_{C,max} = 4.6439) \rightarrow VI = 0.0915$

Table 2. Betweenness centralities for the second case study

Node	C_B	PC_B	Node	C_B	PC_B
1	0.0953	0.0336	14	0.0621	0.0219
2	0.0833	0.0294	15	0.2127	0.0749
3	0.0973	0.0343	16	0.2607	0.0918
4	0.0201	0.0071	17	0.2299	0.081
5	0.1796	0.0633	18	0.0821	0.029
6	0.1999	0.0704	19	0.0033	0.0012
7	0.1884	0.0664	20	0.0276	0.0098
8	0.0229	0.0081	21	0.0546	0.0193
9	0.0560	0.0198	22	0.1508	0.0532
10	0.1996	0.0703	23	0.0622	0.022
11	0.2416	0.0851	24	0.0217	0.0077
12	0.2176	0.0767	25	0.0039	0.0014
13	0.0667	0.0235			

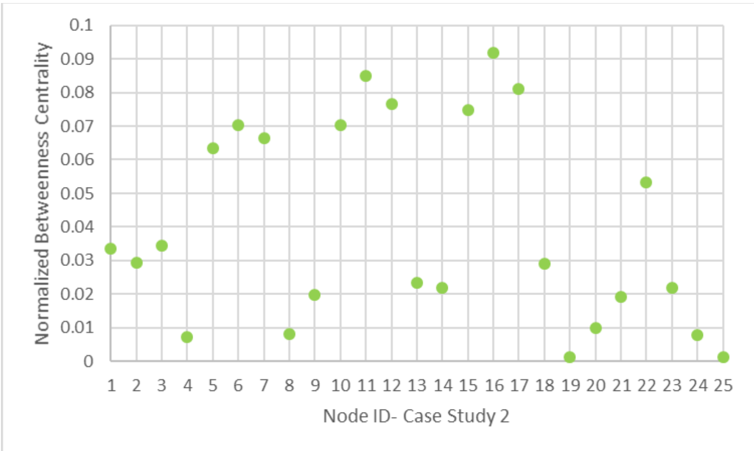

Fig. 4. Normalized betweenness centralities of nodes- case study 2

What is particularly striking about the contrast between two case studies is that the first case study produces a highly heterogeneous distribution of the normalized betweenness centrality values, whereas the second case study presents a rather homogeneous distribution of the nodal centralities. The resulting vulnerability index in the second case study is therefore far lesser than that of the first case study. This proves that the proposed vulnerability index captures the distinctions between the tree-shaped networks, where water can take only one pathway from the source to the households and the looped WDNs, where water flows from the source node to the households thorough many pathways. Loosely speaking, VI measures the risk to satisfactory level of water supply service. The larger vulnerability index the larger magnitude of the failure, as such the consequences of disruptive events on the network performance in the first case study has been precisely captured by a higher vulnerability index when compared to the second case study. This observation conforms to the intuition of the vulnerability concept discussed throughout this paper.

5. Conclusions

The present paper attempts to fill the gap surrounding the topological vulnerability analysis of WDNs. In doing so, we introduce a two-step procedure for quantifying the vulnerability by integrating the centrality analysis and the entropy theory.

In the first step, the paper evaluates the degree of influence of a node by employing a graph theory quantity known as the betweenness centrality. In the second step, this work has drawn attention to the information entropy as a tool to measure the homogeneity and heterogeneity of the betweenness centrality values, computed in the first step.

This article generates a new vulnerability index as a measure of the global vulnerability of WDNs. The new vulnerability index is developed from the information entropy based on the distribution of the normalized betweenness centrality values. The new index measures the severity of the consequences of the random nodal failures. The vulnerability analysis results showed that the failure of a highly central node leads to a significant loss of the performance in the network.

Using two case studies, a tree-shaped WDN and a looped network from the literature, this paper has demonstrated the effectiveness of the proposed method. As the previous discussion attests, the proposed vulnerability analysis method is in consistent with the intuitive notion of vulnerability.

As part of the first practical implication, the maintenance strategy based on the vulnerability analysis proposed herein will provide an expert facilitator that helps water utilities to identify and prioritize the vulnerabilities. The second practical implication is especially valuable for designing an effective risk management framework, which allows for least cost decisions to be made for the protection of the WDNs.

This article contributes to the vulnerability analysis of water distribution network by coupling the centrality analysis and the entropy theory. However, the conventional centrality measures rely only on the topological information. As such, these measures only partially describe a network structure and therefore cannot entirely characterize its properties. Further research might seek to develop a domain specific centrality metrics taking into account the topological along with the hydraulic attributes of the nodes in the network.

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