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Robustness and vulnerability assessment of water networks by use of centrality metrics

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Abstract: The reliability of a water distribution network (WDN) is a function of several time-invariant and time-dependent factors affecting its components and connectivity, most important of which have been shown to be the network's topology, its operating pressure, the type of key components (such as the diameter, length, material and age of water pipes) and the network's historical performance (such as the number of previously observed failures in the network). In terms of network topology, this attribute even though generally thought as time-invariant it actually is time-dependent, as the paths in a water distribution network change over time based on the hydraulics in the network (water demand and water pressure/flow alter the way water flows in the piping network). The work described herein examines the time-dependent nature of a WDN topology and by means of a betweenness centrality index (BC) method demonstrates the effect of topology on the network's vulnerability / reliability. The importance of the BC index is demonstrated by use of a case-study water distribution network operated under both normal and abnormal conditions. The proposed method is also coupled with spatial mapping to indicate areas of concern in the network, and with a decision support system to assist in prioritizing actions to improve on the network's robustness and resilience.

Key words: Network robustness; Vulnerability assessment; Pipe breakage

1. INTRODUCTION

One of the biggest challenges faced by water authorities is the management of their WDN, especially in light of the increasing network complexity and of the increasing rate of pipe deterioration. As a result, it is becoming increasingly important to being able to assess the network reliability and resilience to catastrophic events by use of management tools. The management system of a well-organized WDN includes decision support systems (DSS) to assess the pipeline system condition and the extent of damage due to pipe failures. The development of these tools requires installation within the network of monitoring devices and sensors, hydraulic simulation models, extended database, geographical in-formation systems (GIS) and mathematical models that simulate the behavior of the WDN through time (Figure 1).

The development of an integrated tool for condition assessment of WDNs is an expensive, time consuming and multi-faceted procedure which, despite its complexity, most times fails to reflect in great detail the actual real-time behavior of network operation. Further, the development, operations and maintenance of the underlying hydraulic and mathematical tools require specialized knowledge, not typically found within the water agencies, and analysis of real-time WDN operational data that hinder the applicability of the models. These aforementioned difficulties give rise to the need for an automated early-stage appraisal system of a WDN's vulnerability, based on the WDN's topological characteristics, which could then be easily amended with additional information for a more holistic vulnerability model. Such information are the hydraulic characteristics and past network performance under normal and abnormal operating conditions (Agathokleous 2015).

The goal of the research work presented herein is the development of a model that: (a) it is cost efficient; (b) its use does not require hydraulic and mathematical knowledge and advanced software skills; (c) it does not require operational data beyond the topography of the WDN; (d) it can lead to reliable conclusions within a short time; (e) it can also be used as a management tool for designing the operation mode of a WDN.

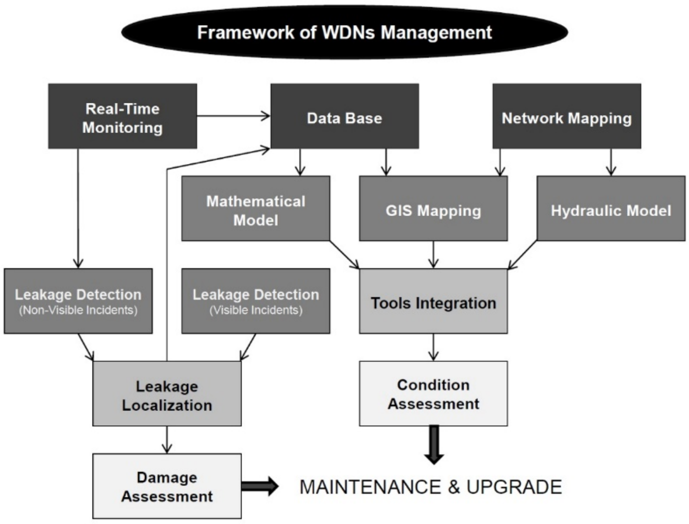


Figure 1. Schematic framework of a WDN management system.

The paper proposes a model based on the principle that the sections of a WDN which are hubs and support large segments of the pipeline system, are subject to stresses whose size is of greater intensity and frequency relative to other network sections, thus being more vulnerable to failure. The importance of each node, relative to the other nodes, with regards to its contribution to the provided network service is computed factoring in the topology of the WDN as described by a betweenness centrality (BC) metric. Finally, for validating the applicability and accuracy of the proposed model, the deduced by the model spatial risk levels (BC weighted graph) are compared to corresponding maps created by the use of actual WDN failure data (pipe bursts).

1.1 Case-study network

The case-study network utilized in the analysis is a District Metered Area (DMA) from the WDN of the city of Nicosia (Cyprus). The studied DMA (DMA6) is divided into 4 sub-district metered areas (Sub-DMAs) and it is remotely monitored through a supervisory control and data acquisition (SCADA) system across the DMA, which continually collects and transmits operational information. All leakage incident data reports since 2003 had been maintained in a specially designed database. The data utilized for verification / validation purposes of the proposed model, covers the time period from 01/01/2003 to 31/12/2010 and includes 548 incidents associated with water mains (WM).

2. STATE OF KNOWLEDGE

2.1 Condition assessment models for WDNs

To date, several mathematical models simulating the operations and condition of WDNs have been developed. Initial research efforts were based on the development of a single-objective mathematical model expressing the failure pattern or system reliability, while subsequent studies expanded the work by presenting multi-objective failure models. More recent efforts focused on the development of models simulating WDN behavior. Finally some recent research activities focused on abnormal operating conditions due to exogenous factors that affect the condition of the network.

Kleiner and Rajani (2001) provide an overview of the mathematical models related to structural deterioration of the WDNs, with the different models grouped into classes according to the governing equations and the types of data that are required for the implementation of each model. Michaud and Apostolakis (2006) presented a scenario-based methodology for the ranking of the elements of a WDN, based on multi-attribute utility theory and a graph theory-based network analysis algorithm. The researchers modelled the system as a network and evaluated the consequences of the failure of each of the network's elements to the supply level, considering the capacity of the elements' connection to the available resources.

Christodoulou (2010) presented a framework for a risk-based integrity-monitoring strategy for the management of WDNs, based on a combination of artificial neural network, parametric and nonparametric survival analysis. In their work, Martinez-Rodriguez et al. (2011) noted that the concept of reliability had been introduced in an attempt to quantitatively measure the possibility of maintaining an adequate service for a given period, and that numerous researchers had considered reliability as a measure of redundancy. A methodology presented by Aydin (2014) uses performance criteria (resiliency, reliability and vulnerability) for evaluating sustainability indices for each node, in terms of nodal pressure and water age. This calculation identifies problematic nodes individually. Shuang (2014) evaluated the nodal vulnerability of WDNs under cascading failures, by use of monitored pressures in different nodes and flows in different pipes which are then used to estimate the network topological structure and the consequences of nodal failure.

In the works of Christodoulou and Fragiadakis (2014) and Fragiadakis et al. (2016) a methodology was presented for the seismic and hydraulic assessment of the reliability of WDNs based on general seismic assessment standards, localized historical records of critical risk-of-failure metrics, and hydraulic simulations using adapted EPANET models. Agathokleous and Christodoulou (2016) investigate the effects of IWS on the condition and breakage rate of WDN, by studying the change in the rate of occurrence of failures before, during and after IWS periods, using statistical and survival analyses. The researchers concluded that IWS practices negatively affect the vulnerability of WDNs.

2.2 Betweenness centrality (BC)

The centrality metric is the most widely used indicator for identifying important nodes of a network based on topological characteristics. Centrality is given in terms of a real valued function for each network node (vertices of a graph), and the resulting values provide a ranking which identifies the most important nodes (Bonacich 1987, Borgatti 2005). The ease in calculation of the centrality metric depends on the net-work size (number of vertices and edges), the connectivity of vertices (number of edges linked on each vertex, directed / undirected edges and connected / disconnected vertices) and the weights as-signed to the edges (Opsahl et al. 2010).

BC is an indicator for identifying the vertices of a network that have high contribution to the transfer of items within the network, and it is equal to the degree of which a vertex falls on the shortest path between the other vertices (Freeman 1977). Mathematically, the BC of a vertex, u, is defined by (Anthonisse 1971):

$$C_B(u) = \sum_{s \neq u \neq t} \frac{\sigma_{st}(u)}{\sigma_{st}} \tag{1}$$

where σ_{st} is the total number of shortest paths from vertex s to vertex t and $\sigma_{st}(u)$ is the number of those paths that pass through u.

3. ANALYSIS, RESULTS AND DISCUSSION

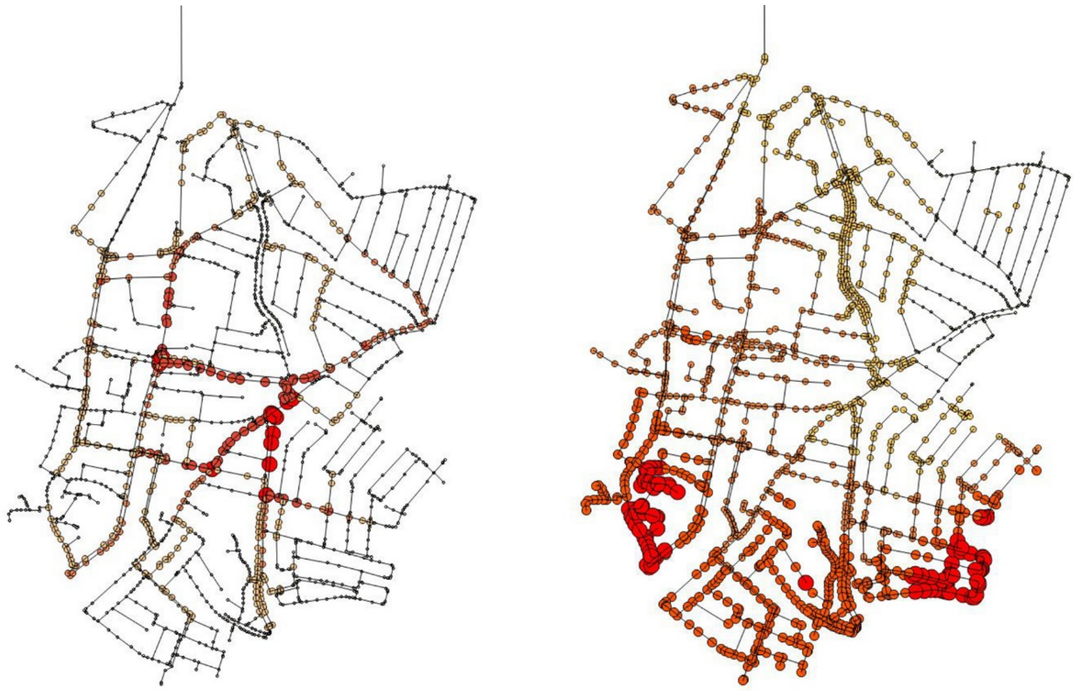
3.1 Pipeline system of DMA6 and vulnerability during continuous water supply

The WDN in study is first analyzed topologically, with BC metrics computed for every node in the network and geographically mapped. The result of the analysis is then spatially mapped using a weighted graph, showing the levels of the BC index across the case-study DMA (Figure 2a).

The areas of high BC values (shown in red) indicate the nodes through which a high number of origin-to-destination paths passes, when considering only the topology of the network. As expected, BC numbers are lower on the periphery of the network, and increase towards its center.

The WDN in study is then analyzed under normal (continuous water flow) operating conditions (data period before March 2008). For this, the continuous water supply (CWS) mode, the BC metrics are computed in conjunction with the underlying hydraulic model for the DMA. That is, the hydraulic model and the deduced nodal pressures and pipe water flows in essence dictate the origin-to-destination paths for every calculation and thus affect the BC computation. As with the previous case, the result of the analysis is then spatially mapped by use of a heatmap, showing the levels of the BC index across the case-study DMA (Figure 2b).

A comparison between Figures 2a and 2b shows the difference in the spatial allocation of the nodal BC indices and of the resulting network vulnerability, when the hydraulic behavior of the DMA under continuous water supply operations is considered. Now the BC values are higher along major water mains, as the deduced water flows at the nodes along these pipes create more water pathways passing through these nodes. Noteworthy is also the fact that the change in network vulnerability (Figure 2b) is actually obtained by opening/closing 9 valves (nodes) in the original network (Figure 2a). This change in vulnerability indicates the effects of hydraulics on the network performance.



(a) *(b)*

Figure 2. Betweenness centrality weighted graph for: (a) Network topology, (b) Continuous water supply (CWS) operations.

3.2 Vulnerability heatmap of intermittent water supply (IWS)

When in abnormal operating conditions (such as IWS operations), the network in study exhibits a different behaviour, with the BC indices varying compared to the ones deduced for the CWS operations (Figure 2b). Under IWS operations (data period after March 2008), the DMA in study is subdivided into four sub-DMAs, each receiving water for 12 hours every 48 hours. During this operation mode the BC indices change, depending on which sub-DMA is active (Figure 3) and how the varying water flow affects the water pathways and the origin-destination pairs in the network.

As with the CWS case (Figure 2b), the BC metrics are computed in conjunction with the underlying hydraulic model for the sub-DMA, and the deduced water flows in the piping network dictate the origin-to-destination paths in the network, thus affecting the computation of the nodal BC indices.

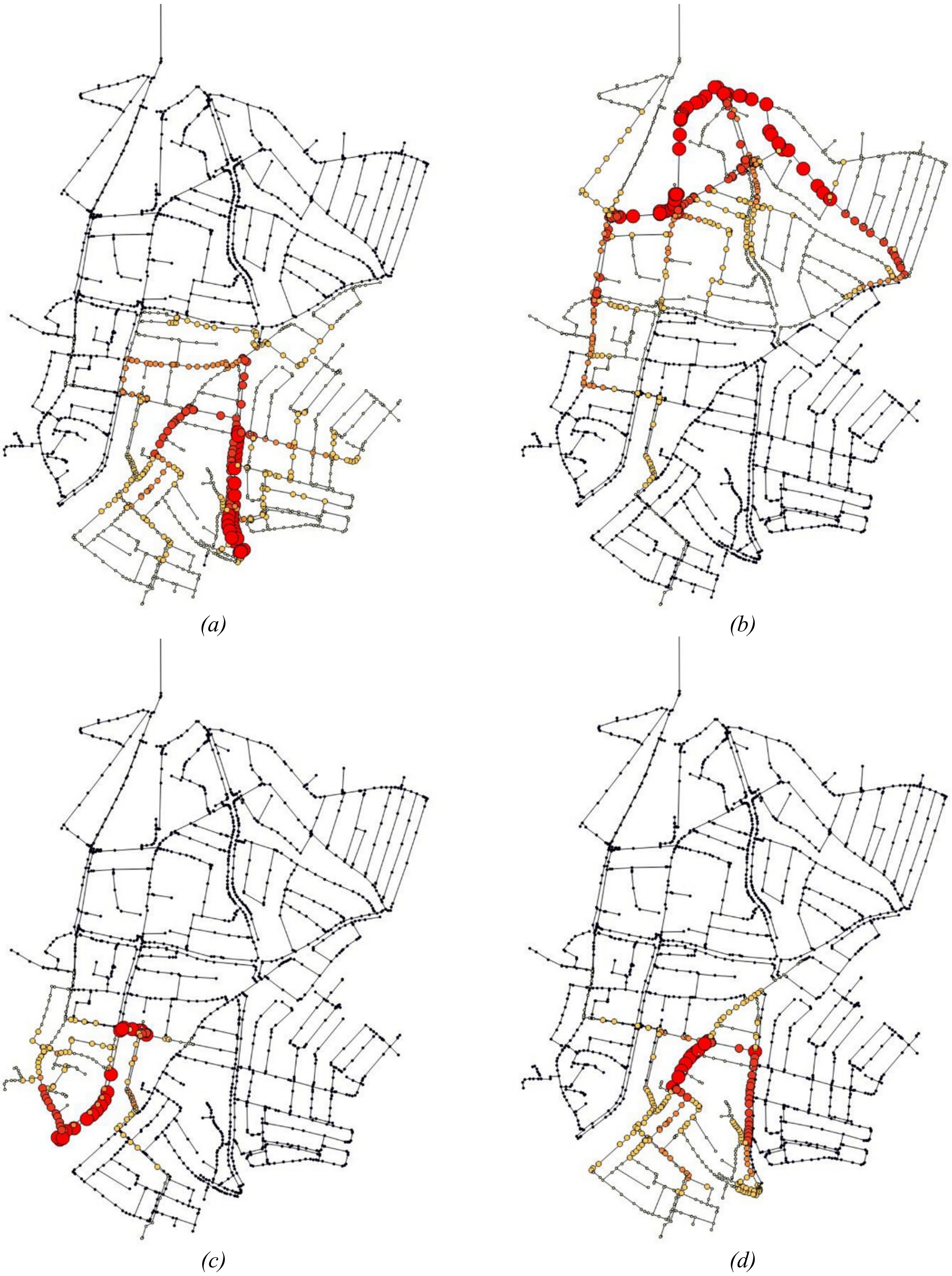


Figure 3. Betweenness centrality weighted graph for the intermittent water supply operation. (a) Sub-DMA 6A, (b) Sub-DMA 6B, (c) Sub-DMA 6C, (d) Sub-DMA 6D.

3.3 Spatial distribution of the failure incidents

The results of shifting in the BC indices as a result of the change in the water supply operations (from CWS to IWS) can be seen in Figure 4, depicting the failure incidents in the WDN in study during the time periods of CWS and IWS. Figure 5 illustrates the heat-maps generated using the failure incidents number, presented by Figure 4.

As can be seen in Figure 5, the spatial distribution of the failure incidents changes as the mode of operations changes, and the centre of gravity shifts as the failure incidents cluster around regions of high BC indices.

This spatial shift and the observed clustering can be attributed to the 'reorganization' of the WDN, as evidenced by the BC weighted graphs, stemming from the changes in water flow/pressure across the network.

(a) (b)

Figure 4. Failure incidents (pipe breaks) in studied WDN: (a) during CWS operations (before March 2008); (b) during IWS operations (after March 2008).

(a) (b)

Figure 5. Heat-maps of failure incidents (pipe breaks) in studied WDN: (a) during CWS operations (before March 2008); (b) during IWS operations (after March 2008).

4. CONCLUSION

The work presented herein provides evidence of the links between the behavior of a WDN under varying operating conditions, the BC indices of the network's nodes, and the network's vulnerability. Given these links, WDN operators can forecast a WDN's behavior under several scenarios and plan for them, optimizing the behavior of the WDN and minimizing its vulnerability against endogenous and exogenous threats, without the need for dynamic hydraulic models. Furth research work is currently under way to link the observed fragility of a WDN with its BC characteristics, using a larger dataset (higher number of incidents, and longer time periods).

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