CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

# Multi-attribute Metric for Assessing Resilience of Water Distribution Networks

Assad, Ahmed[1,4] Osama Moselhi[2], and Tarek Zayed[3]
[1] Ph.D. Candidate, Concordia University, Canada.
[2] Professor, Concordia University, Canada.
[3] Professor, Hong Kong Polytechnic University.
[4] ahmed.assad@mail.concordia.ca

**Abstract:** Ensuring a proper function of water systems has always been a major concern for utilities and municipalities because of their direct impact on public health and safety. Resilience assessment of these networks is emerging as an important requirement in planning and management of Water distribution networks (WDNs). In this context, it is desirable for water networks to be strong enough to withstand disruptions with least impact on their performance and to enable fast recovery in case of service loss. Several models have been developed to consider resilience in design of WDNs, but much less in their operation and maintenance. Those that targeted operation and maintenance were limited to one source of hazards like earthquakes. The ultimate objective of a current research is to develop a holistic resilience-based management method for water distribution networks. This paper presents a newly proposed metric to assess resilience of WDNs considering multi-hazard events. A detailed framework and algorithm are developed to estimate loss in resilience arising from a given source of hazard. The metric is based on two components robustness and redundancy. Robustness of WDNs is modeled by integrating reliability and criticality of its water mains. Graph theory is employed to quantify the connectivity and redundancy in the network. The metric is then formulated as a weighted sum of the two components. Several codes were developed to capture a scenario-based assessment of various hazard events. Data from City of London, ON was fetched to implement the developed model. The results will identify the critical components of the network which are responsible for a total service loss. This type of output can be of help to decision makers in setting priorities for maintenance of their WDNs.

## 1 Introduction

Following any hazard, water infrastructures play a dominant role in firefighting and rescue efforts. Hence, maintaining the functionality of such critical systems is of a paramount importance after any hazard event or disruption (Farahmandfar et al. 2016). While the traditional focus was on the physical protection of water systems, the emerging trend is highly raising the issue of resilience. The American Society of Civil Engineers defines the resilience of infrastructure as the ability to mitigate all-hazard risks and rapidly recover critical services with minimum harm to the public safety, health, economy and national security (Ayyub 2014). In this context, it is desirable for the water networks to be strong enough to withstand any disruption with a minimum impact on its performance and to recover quickly in case of service loss (Cimellaro et al. 2015). Consequently, there has been a rapidly increasing attention both, in practice and academia, to define resilience and derive quantifiable resilience metrics. The literature includes several frameworks that have been developed to include during the design and operation of civil infrastructures.

Nevertheless, most of the previous work focused on a single hazard event instead of assessing the resilience of water assets to multi-hazard events. Moreover, there are very limited efforts that consider the various aspects and parameters of WDNs resilience. Therefore, this paper introducers a comprehensive resilience assessment framework to evaluate resilience of water networks.

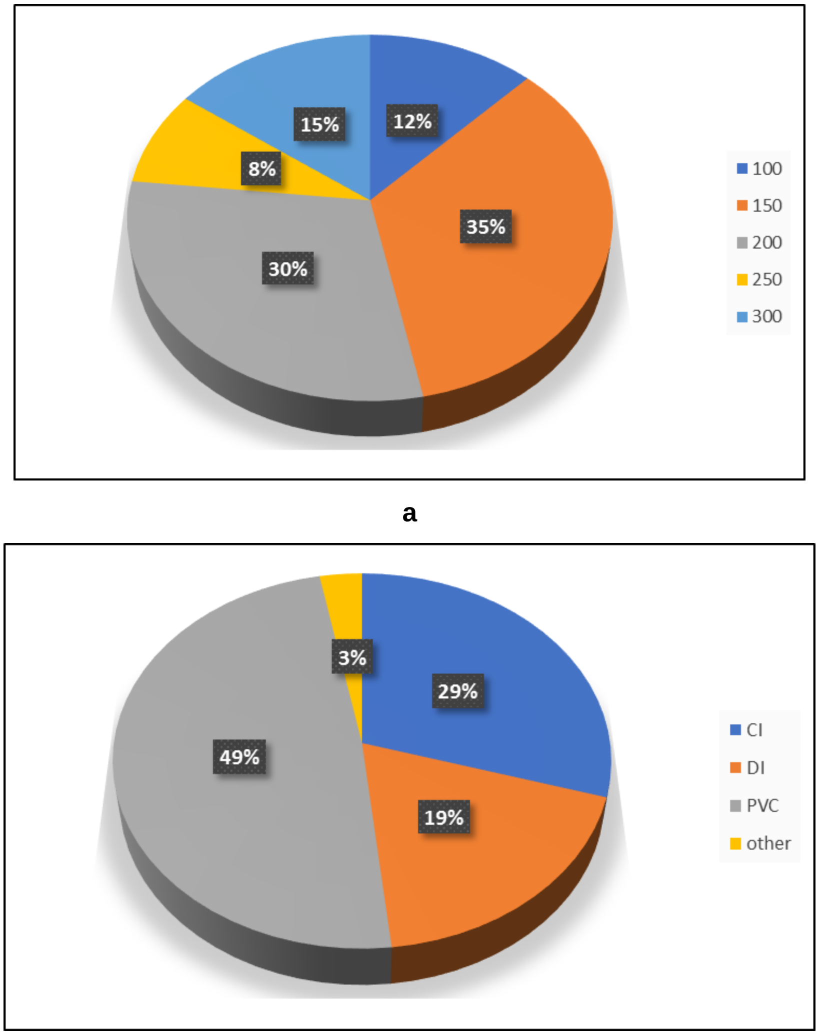
## 2 Background

Reviewing the literature reveals two main approaches for measuring and assessing resilience of water networks: qualitative approaches and quantitative approaches. Most of the qualitative approaches comprise listing resilience attributes, assigning them numerical weights, and then aggregating these weighted metrics into a single composite index. The main drawback of this approach is ignoring the relations between the indicators. Fisher et al. (2010) introduced a resilience index to measure the resilience of critical infrastructures including water systems. The model required extensive data collection about 1,500 variables categorized under robustness, recovery, and resourcefulness. The variables were then weighted and summed to generate a single global resilience index that facilitates the comparison between different infrastructure systems (Fisher et al. 2010). Such approaches are usually subjective, and the results cannot be generalized on a large scale. Quantitative approaches of resilience assessing involve modeling the impact of a specific hazard on the network. Such approaches account for two main components of resilience: the hazard severity and the system response. Some studies employed resilience as a system property and aimed to investigate the dynamic relations between the components of the system. Jayaram and Srinivasan (2008) formulated a resilience assessment model that accounts for multiple sources within a network, a major limitation of Todini's model (Jayaram and Srinivasan 2008). Gay and Sinha (2013) integrated MATLAB and EPANET2 software packages to develop a stochastic simulation-based methodology to assess the resilience of water distribution system. Simulations were run to quantify the performance loss, recovery time and recovery cost following a hazard event (Gay and Sinha 2013). Another quantitative approach to evaluate system's resilience employs it as the opposite of the system's vulnerability to various disruptions. Principles of graph theory were utilized in many of these approaches to model the water network as nodes and links (Farahmandfar et al. 2016). Despite the previous efforts in trying to address the performance assessment of water networks, several draw backs can be realized. Most of the previous efforts investigated the resilience of WDNs to a certain and specific hazard such as earthquakes or floods. There is a need for a comprehensive approach that shifts the emphasize from analysis of separate threats toward quantifying the impact of such hazards on the WDNs and how they response to different resorting polices. The key advantage in this approach is the ability to address many hazards that result in the same failure mode in one single analysis. Accordingly, this study is proposing a new resilience metric that can be used to assess resilience of WDNs against various types of hazards.

## 3 Developed Resilience Metric

The developed resilience metric accounts for robustness and redundancy of WDNs. This metric allows users to define the relative importance of each of those components. the data needed to develop and test this metric was collected from the City of London, ON. The City of London was incorporated in 1855 and rapidly established itself as a business hub in southern Ontario. The City owns a water network of more than 24,000 mains some of them were installed back in 1900 and still active till today. Figure 1 shows that over 97% of the City's network is either cast iron, ductile iron, or PVC with diameter size <300mm. The City of London shared their data base inventory with the authors for the purpose of this research. The extracted data include data related to the characteristics of the pipeline, installation data, surrounding environmental condition, and breakage data. The breakage data include the order, time, and type of each observed break in the network. All the data were provided as GIS layers.

Robustness of WDN is its ability to withstand disaster forces without significant degradation. Two models are integrated to capture the robustness of WDNs: i) reliability model and ii) criticality model. Robustness of a WDN is measured by the reliability of its water mains. A deteriorated pipe segment with long failure history is more vulnerable to even light



a

b

Figure 1 : Distribution of Pipe a) size b) material

disruptions. Robustness is calculated as the sum of reliabilities of all the connected pipe segments. Mechanical reliability is chosen as the basis of establishing this metric as it is the best to describe the structural performance of WDN during several disruptions. Individual pipe segment criticality is added as a weight to prioritize segments of higher criticality. For a network that consist of several pipe segments, the most critical segments are the most important ones in determining its performance. Finally, the weighted formulation is normalized to reflect the extreme cases when the reliability is either at its maximum or minimum bounds. For example, pipe segments that are highly reliable and of low criticality are more robust than those of low reliability and high criticality. The formulation of this metric as a multiplication of reliability and criticality is mathematically valid as these two variables are independent (e.g. a water main can be highly reliable and at the same time of a low criticality and vice versa). Redundancy on the other hand, is the extent to which a system is capable of satisfying functional requirements, if significant degradation occurs. Redundancy improves the network's connectivity and makes it more failure-tolerant. Meshed-ness Rm can then be calculated as the ratio of the total number to the maximum number of independent loops in the planar graph. Resilience metric is finally calculated as a weighted sum of the robustness and redundancy. considering the aforementioned formulation for each, the proposed resilience metric is given by equation 1:

$$[1]\ Я = w_1 \times \frac{\sum_{i=1}^{P} R_{\,i} \times C_{\,i}}{\sum_{i=1}^{n} C_{\,i}} + w_2 \times \frac{m-n-1}{2n-5}$$

Where Я is the metric used to assess the resilience of WDN, $R_i$ is the reliability of water pipe segment i, $C_i$ is the criticality index of water pipe segment i, P is the total number of pipe segments, n is the network size, m is the network order when presented as graph G, $w_1$, and $w_2$ are relative weights.

Applying the model on a section of London WDN, referred as LWDN, to calculate the resilience level. The redundancy is found to be 0.1016 which indicated a very poor connectivity level, scattered network's structure. Resilience of LWDN is found by adding the redundancy of the network to its robustness, each multiplied by a relative weight. Resilience of LWDN is given in Table 1. Resilience of LWDN is less than 25%. The relative weights of robustness and redundancy that were used in estimating the resilience of LWDN are 80% and 20% respectively. These weights can be changed based on the preference of the decision maker at the municipality of the utility managing the operation and maintenance of the network. Figure 2 shows the results of a sensitivity analysis in which the weights of robustness in equation 1, and accordingly weights of redundancy, was changed from 100% to 0%.

Table 1: Robustness and Resilience of LWDN

| Year | Resilience (t) |
|---|---|
| 0 | 0.236 |
| 1 | 0.212 |
| 2 | 0.189 |
| 3 | 0.169 |
| 4 | 0.150 |
| 5 | 0.133 |

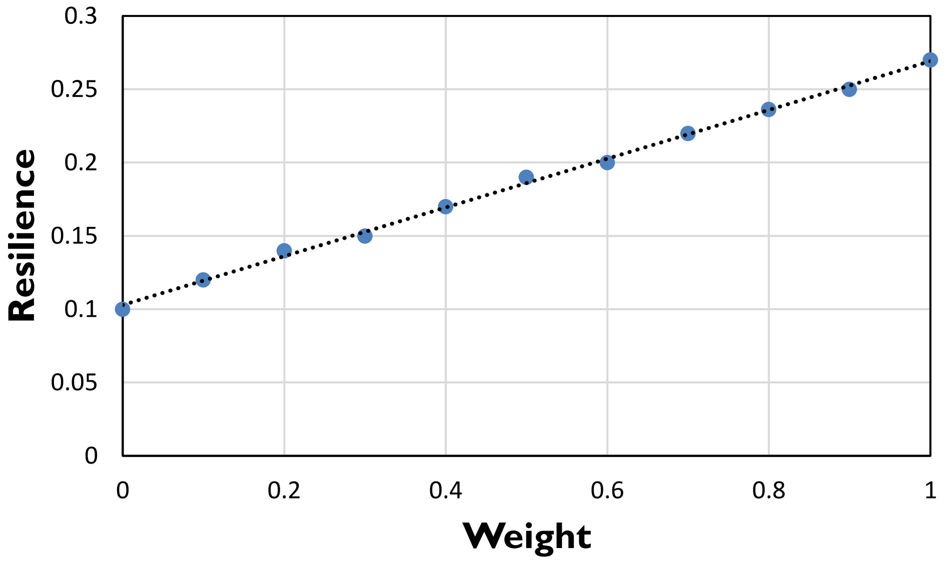


Figure 2: Effect of changing robustness's weight on resilience

## 4 Conclusion

In this research, a multiattribute resilience metric is developed based on robustness and redundancy of WDNs. Reliability and criticality of water segments along with several parameters from graph theory are employed for the purpose of developing this metric. By incorporating these attributes, the proposed resilience metric is able to capture the technical, social, and economic aspects of resilience. Several factors for quantifying each of these dimensions were considered and aggregated to develop the resilience metric. This metric is expected to contribute in providing a holistic decision support system for decision makers and key personal who in charge of evaluating, assessing, and enhancing the functionality and resilience of water distribution networks. This model is also useful in anticipating the optimum order of resorting activities to minimize the time of service disruption in presence of a set of operational and social constraints.

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