engineering proceedings

Proceeding Paper

Comparative Risk Evaluation of Contaminant Intrusion in Water Distribution Networks via Complex Network Analysis †

Jordana Alaggio [1], Daniel Bezerra Barros [2], Bruno Brentan [1,*] and Gustavo Meirelles [1]

1 Hydraulic and Water Resources Department, Federal University of Minas Gerais (UFMG), Belo Horizonte 31270-901, Brazil; jordanaalaggio@gmail.com (J.A.); gustavo.meirelles@ehr.ufmg.br (G.M.)
2 Water and Energy Resources Department, University of Campinas (UNICAMP), Campinas 13083-970, Brazil; danielbezerrab@gmail.com
* Correspondence: brentan@ehr.ufmg.br; Tel.: +55-3198298-6823
† Presented at the 3rd International Joint Conference on Water Distribution Systems Analysis & Computing and Control for the Water Industry (WDSA/CCWI 2024), Ferrara, Italy, 1–4 July 2024.

Abstract: Water distribution networks (WDNs) aim to ensure uninterrupted delivery of high-quality water; however, they are susceptible to failures that can compromise water quality. Decision-makers need to pinpoint crucial network components to optimize maintenance and improve system efficiency. This research investigates the risks of contaminant intrusion in WDNs. Complex network theory (CNT) provides an alternative approach by modeling WDNs as complex networks and analyzing network dynamics, contaminant propagation, and critical elements. EPANET software simulates contamination, while CNT metrics assess node influence. Our findings demonstrate the compatibility and potential hybrid form to work with these methodologies, offering a more efficient approach to WDN risk management.

Keywords: risk map; contaminant intrusion; quality simulation; complex network theory; graph theory

Citation: Alaggio, J.; Barros, D.B.; Brentan, B.; Meirelles, G. Comparative Risk Evaluation of Contaminant Intrusion in Water Distribution Networks via Complex Network Analysis. *Eng. Proc.* **2024**, *69*, 65. https://doi.org/10.3390/engproc2024069065

Academic Editors: Stefano Alvisi, Marco Franchini, Valentina Marsili and Filippo Mazzoni

Published: 4 September 2024

1. Introduction

The occurrence of contamination of Water Distribution Networks (WDNs) involves several factors, with the proximity of contaminant sources to the network, the presence of a driving force, and structural failures being the most significant ones [1]. Changes in operational conditions, such as variations in pump operation, opening or closing of valves, or abrupt changes in consumption, can induce transient events, resulting in pressure variations that allow contaminants to enter the network.

In this context, conducting contaminant intrusion risk analysis plays a crucial role in assisting decision-makers in adopting preventive measures and efficiently allocating resources, thereby providing a better understanding of the network [2,3]. Traditionally, risk analysis has been conducted through hydraulic simulations [4].

The Complex Networks Theory (CNT) has become a valuable tool for interpreting and comprehending intricate urban systems, including water supply systems. The evaluation of networks through graph theory is a fundamental aspect of mathematics but encompasses various key areas. These included research on sizing optimization, leak detection methodologies, investigations into network resilience, spectral techniques, optimal sensor placement for contaminant intrusion detection, and the optimal partitioning of network infrastructure [5].

This study aims to analyze the potential consequences of failures in the WDN due to their significant impact. The primary objective is to identify the most critical elements within the network where contamination could have far-reaching effects on a substantial number of consumers and broader geographical areas. Several metrics related to the evaluation of critical elements in the network are applied. Graphs are modeled considering the direction and weighting of graph edges, as well as distinguishing between vertices representing demand nodes and water source nodes (reservoirs). Comparisons between the modeling techniques employed in this study and those found in reference networks from the literature were made to enhance the understanding of the WDN's complexity and critical elements.

2. Methodology

The proposed methodology is structured into two distinct stages. The initial phase of the methodology entails conducting water quality simulations, a task facilitated by the utilization of the software EPANET 2.2 [6]. Within this simulation framework, it becomes imperative to ascertain various parameters such as the concentration of the substance, reaction coefficients, type of contamination source, and the simulation period. The introduction of the individual contaminant occurred by injecting it into each node of the network for a duration of 1 h out of the total 24 h of simulation, a timeframe deemed adequate for system recovery. To assess the criticality of a node, the focus was on quantifying the nodes impacted by each intrusion, specifically those nodes exhibiting a concentration exceeding 0 mg/L of the substance during the simulation.

Transitioning to the second stage, the methodology incorporates the use of CNT. Within this stage, the WDN is conceptualized as a graph, and CNT metrics are subsequently computed. A graph can be effectively represented through an adjacency matrix, which delineates the connectivity between vertices [7].

The analysis conducted in this study involved a directed and weighted graph with values based on average flow values derived from a single hydraulic simulation of the network, devoid of any failures. Source–demand betweenness centrality [8] is employed in this study, with the centrality of a vertex v computed as the summation of shortest paths between a vertex s from the water sources set and a vertex z from the demand nodes set, passing through vertex v across all shortest paths between s and z, as depicted in Equation (1).

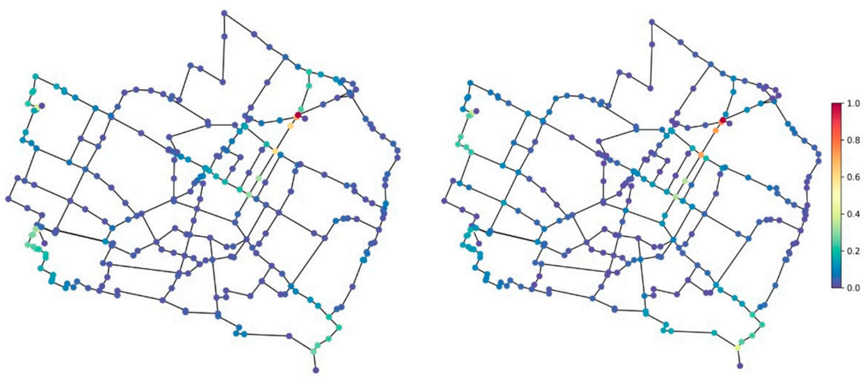
$$C_b = \sum_{s \in S,\ z \in Z} \frac{\sigma(s, z|v)}{\sigma(s, z)} \tag{1}$$

The centrality metric was utilized to pinpoint the most influential node within the network, with the objective of determining the node whose contamination would have the most significant impact on a wider area. Following this, the outcomes derived from the two phases were juxtaposed both quantitatively and by generating risk maps, with the aim of conducting a thorough and methodical examination of the scenario under investigation. All procedures and findings were scrutinized within the Python programming framework, leveraging the Water Network Tools for Resilience (WNTR) [9] and NetworkX [10] libraries for support.

3. Results

The research methodology was implemented on two networks characterized by varying sizes and complexities. Initially, the Modena network, classified as a medium-sized network, was utilized, followed by the subsequent analysis on the E-Town network.

In order to compare the outcomes derived from the application of the methodology across the two network instances, risk maps were constructed, as illustrated in Figure 1. Within this visual representation, both risk maps underwent a normalization process. Notably, the risk map resulting from the contaminant insertion scenarios exhibited a distinctive feature where nodes appearing in a redder hue indicated a higher criticality to contamination, signifying a greater number of nodes affected by the introduced substance. Conversely, in the risk map pertaining to the second stage of analysis, nodes depicted in a deeper shade of red denoted an elevated value of the source–demand betweenness centrality metric. This metric signifies the extent to which a particular node is integrated into the shortest paths within the network structure.

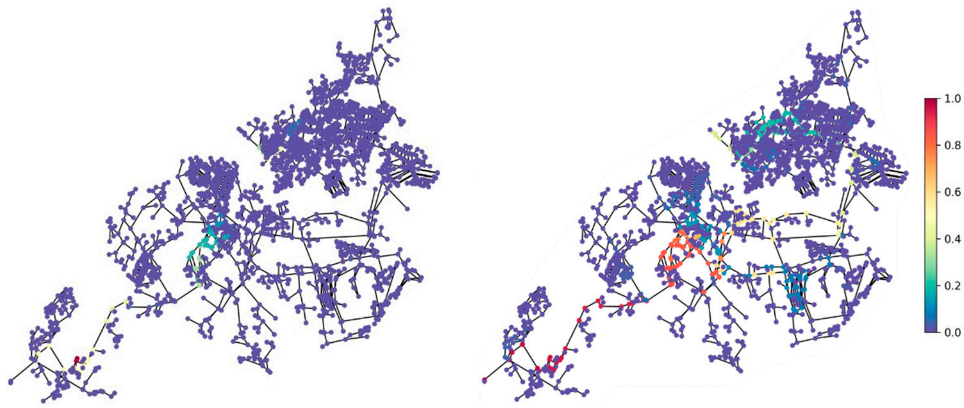


(**a**) (**b**)

Figure 1. Risk maps of Modena network normalized: (**a**) based on quality simulation, where the most important node is the one that carried out more contaminant to other nodes; (**b**) based on CNT applied in a directed and weighted graph, where the most influential node is the one with the biggest value of source–node betweenness centrality.

Through the construction of risk maps, the convergence between the two stages became apparent, highlighting specific areas in close proximity to the network's reservoirs, which are already recognized as significant. This observation suggests a representation that mirrors the behavior of the Modena network. The efficacy of the metric was evaluated within an undirected graph, revealing additional critical areas that diverged from the outcomes predicted by the quality simulation scenarios.

Upon implementing the initial stage of the methodology on the E-Town network, the risk maps depicted in Figure 2 were generated.



(**a**) (**b**)

Figure 2. Risk maps of E-Town network normalized, based on quality simulations: (**a**) how many nodes were affected by the contaminant with the bulk coefficient = −1; (**b**) how many nodes were affected by the contaminant with the bulk coefficient = 0.

The conducted analysis compared the two maps, emphasizing that a mass coefficient of −1 signifies that the substance is interacting with other elements within the water distribution network, leading to a decrease in its concentration. Conversely, a mass coefficient of zero indicates that the substance is inert in the network, and any reduction in its concentration is solely due to consumption. Upon juxtaposing the two maps depicted in Figure 2 with the utilization of the complex network theory metric in a comparable graph of the water distribution network, a higher degree of resemblance was noted with the risk map exhibiting a zero-mass coefficient.

In the comparison between the risk map generated through quality simulation of contaminant intrusion using a mass coefficient of −1 and the outcome derived from metric application, it is noted that only a portion of the pipes identified as critical through the CNT application are also deemed critical in quality simulations. Nevertheless, this designation remains consistent for nodes situated in areas characterized by elevated flows and larger pipe diameters.

4. Conclusions

The utilization of CNT on the graphs yielded satisfactory results, effectively highlighting the crucial components in a manner consistent with the WDN risk analysis conducted through conventional methods. By employing the shortest paths metric, the objective was to differentiate between water source nodes and demand nodes, with the aim of enhancing the correlation between the calculation of this metric and the water flow within the network. During the examination of the vertices, source–demand betweenness centrality emerged as the most suitable metric among several metrics that were tested. It was noted that the application of this metric led to enhanced convergence when comparing the outcomes across different stages: risk maps generated from water quality simulations of failure scenarios, and the implementation of TRC metrics.

Author Contributions: Conceptualization, B.B. and J.A.; methodology, J.A.; software, J.A and D.B.B.; validation, J.A.; writing—original draft preparation, J.A.; writing—review and editing, J.A., G.M. and B.B.; supervision, G.M. and B.B.; funding acquisition, B.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CNPq, grant number 404605/2021-4 and FAPEMIG, grant number APQ-01320-21.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Mansour-Rezaei, S.; Naser, G.; Sadiq, R. Predicting the potential of contaminant intrusion in water distribution systems. *J. AWWA* **2014**, *106*, E105–E115. [CrossRef]
2. Khorshidi, M.S.; Nikoo, M.R.; Sadegh, M. Optimal and objective placement of sensors in water distribution systems using information theory. *Water Res.* **2018**, *143*, 218–228. [CrossRef] [PubMed]
3. Barros, D.B.; Cardoso, S.M.; Oliveira, E.; Brentan, B.; Ribeiro, L. Using data mining techniques to isolate chemical intrusion in water distribution systems. *Environ. Monit. Assess.* **2022**, *194*, 203. [CrossRef] [PubMed]
4. Diao, K.; Sweetapple, C.; Farmani, R.; Fu, G.; Ward, S.; Butler, D. Global resilience analysis of water distribution systems. *Water Res.* **2016**, *106*, 383–393. [CrossRef] [PubMed]
5. Yu, X.; Wu, Y.; Meng, F.; Zhou, X.; Liu, S.; Huang, Y.; Wu, X. A review of graph and complex network theory in water distribution networks: Mathematical foundation, application and prospects. *Water Res.* **2024**, *253*, 121238. [PubMed]
6. Rossman, L.A.; Woo, H.; Tryby, M.; Shang, F.; Janke, R.; Haxton, T. *EPANET 2.2 User Manual*; U.S. Environmental Protection Agency: Cincinnati, OH USA, 2020.
7. Giudicianni, C.; Di Nardo, A.; Di Natale, M.; Greco, R.; Santonastaso, G.; Scala, A. Topological Taxonomy of Water Distribution Networks. *Water* **2018**, *10*, 444. [CrossRef]
8. Brandes, U. On variants of shortest-path betweenness centrality and their generic computation. *Soc. Netw.* **2008**, *30*, 136–145. [CrossRef]
9. Klise, K.A.; Murray, R.; Haxton, T. An Overview of the Water Network Tool for Resilience (WNTR). In Proceedings of the 1st International WDSA/CCWI Joint Conference, Kingston, ON, Canada, 23–25 July 2018.
10. Hagberg, A.; Swart, P.; Schult, D. Exploring Network Structure, Dynamics and Function Using Networkx. In Proceedings of the 7th Python in Science Conference, Pasadena, CA USA, 19–24 August 2008.