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Investigating the Efficacy of Topological Methods for Optimal Sensor Placement in Water Distribution Systems [†]

Ludovica Palma [1,2,*], Armando Di Nardo [2], Fatemeh Hatam [1], Giovanni Francesco Santonastaso [2] and Michèle Prévost [1]

[1] NSERC Industrial Chair in Drinking Water, Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, Montréal, QC H3C 3A7, Canada; fatemeh-2.hatam@polymtl.ca (F.H.); michele.prevost@polymtl.ca (M.P.)
[2] Department of Engineering, Università della Campania Luigi Vanvitelli, 81031 Aversa, Italy; armando.dinardo@unicampania.it (A.D.N.); giovannifrancesco.santonastaso@unicampania.it (G.F.S.)
[*] Correspondence: ludovica.palma@polymtl.ca

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Abstract: Water-distribution networks (WDNs) are vital infrastructure that are exposed to the risk of contamination. Several factors contribute to this risk, including insufficient pressure, contamination in water storage tanks and more. Sensor systems are crucial for detecting contaminations promptly. Traditional optimization methods to define sensor locations often require resource-intensive network modeling, posing challenges for water utilities. This study applies a topological approach using betweenness centrality to address sensor placement. Various weights based on the physical structure of the network are tested. Results highlight the effectiveness of weighted topological approaches in minimizing contamination's public health impact, with the advantage of low computational costs inherent in graph-based network representations.

Keywords: water quality; real-time monitoring; sensor placement; complex network theory

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1. Introduction

WDNs play a crucial role in delivering safe water to inhabitants, underscoring their high importance in ensuring public health. However, guaranteeing water quality within these networks presents significant challenges due to various contamination types that can take place. To safeguard public health and ensure the continuous delivery of safe water, monitoring of WDNs is paramount. Sensor systems offer the capability to assess water quality and detect anomalies promptly. However, determining the optimal placement of sensors remains a complex challenge. Numerous studies have proposed methodologies employing optimization techniques to address this issue [1]. While effective, these methods may be computationally demanding, often involving multiple objective functions and complex hydraulic simulations, making them impractical for large-scale WDNs.

Recent studies have introduced topological methodologies for sensor placement, eliminating the necessity of hydraulic solvers [2–4]. These approaches leverage graph theory to analyze the structural attributes of the network, bypassing the need for simulating contamination scenarios. Consequently, sensor placement remains unaffected by simulated events, offering a more flexible and versatile strategy. The topological approach considers the network as a graph devoid of a priori contamination simulations. This methodology bypasses specific contamination scenarios and focuses exclusively on the structural attributes of the network. As such, sensor placements are not influenced by simulated contamination events, offering a more generalized and adaptable strategy for sensor deployment.

The objective of this study is to define sensor locations utilizing a weighted topological approach. Specifically, five distinct weights are considered, and the outcomes are evaluated by simulating contaminations in a real Italian network.

2. Materials and Methods

To define the location of sensors with the topological approach, the network is represented as a graph G = (V, E), where V represents the set of vertices or nodes and E the edges. In the proposed approach, a weighted and undirected graph is used, where the weights w_{st} are defined for the generic pipe that connects the nodes s and t. The efficiencies of different weights are tested: the relative length $(w_{RL,st})$, the length ($w_{L,st}$), the capacity ($w_{C,st}$), the inverse of the capacity ($w_{1/C,st}$) and diameter ($w_{D,st}$). For comparison reasons, the unweighted graph is also tested.

The diameter (D_{st}) and the length (L_{st}) of a pipe are linked to its hydraulic resistance. Indeed, the resistance coefficient, in commonly used formulas, is a function of $L * D^{\approx -5}$. The weight $w_{D,st}$ is set as equal to D_{st}, while $w_{1/L,st}$ is the inverse of L_{st}. The relative length provides insight into the probability of a segment experiencing service interruptions necessitating repair due to breakage [5]. The weight $w_{RL,st}$ is estimated as the ratio between L_{st} and the total pipe length of the WDN (L_{tot}). The capacity of the pipe estimates the maximum volume of flow passing through the pipe. This parameter offers valuable knowledge about the pipe size, operational costs, construction expenses and maintenance costs [6]. The weight $w_{C,st}$ is assumed to be equal to the area of the pipe and $w_{1/C,st}$ is the inverse.

Once the WDN is represented as a weighted graph, a clustering phase is performed, assuming a number of clusters equal to the number of sensors. Clustering enables the grouping of data points based on their similarity, ensuring that points within the same group exhibit similar characteristics. In the proposed approach, spectral clustering [7] is used. It exploits the spectral properties of an adjacency matrix to segment the data into coherent groups. For each cluster, the sensors' location is defined by employing the edge betweenness centrality. This centrality quantifies the frequency of occurrence of each node along the shortest path between two nodes in the graph. It is important to note that since it uses the shortest path concept, the weights defined before need to be reversed for calculation purposes. In this way, the shortest path will be the one characterized by the highest weight. Finally, for each cluster, the sensor is located in the most central node.

The sensor placement achieved through this method is distinguished by low computational requirements and reliance solely on the physical structure of the WDN. Consequently, it does not necessitate a calibrated hydraulic model, making it readily executable for water utilities [4].

The developed sensor systems are tested via simulations of conservative contaminations. Evaluation metrics consist in the probability of detection $DP = N_{ds}/N_s$ (the ratio of detected scenarios to the total number of simulated scenarios), detection time t_d (the average duration for detecting all scenarios, calculated from the onset of contamination to sensor detection) and the number of exposed users N_{eu}. This represents the number of users exposed to a contaminant's concentration higher than the hazard concentration threshold $C = 0.3$ mg/L [8].

3. Case Study and Results

The testing phase of this study utilizes the real WDN of Giugliano in Campania, a city in southern Italy serving a population of approximately 120,000 people. The network comprises 994 demanding nodes, 5 intake points and 1077 pipes. Contaminations are simulated by introducing a conservative contaminant into each node of the network, resulting in a total of 999 contamination scenarios (N_s). Hydraulic and water quality simulations were conducted using EPANET 2.2, with a total duration of 4 days. The contaminations are simulated at 11:00 on the fourth day to ensure hydraulic stability across all network nodes.

The contaminant is injected in single nodes as a mass source, with an injection flow rate of 125 L/h and a contaminant concentration of 230,000 mg/L [8] with a total duration of 1 h. The municipality of Giugliano established nine sampling points across the WDN, so the locations of nine sensors with the topological approaches are defined (Figure 1).

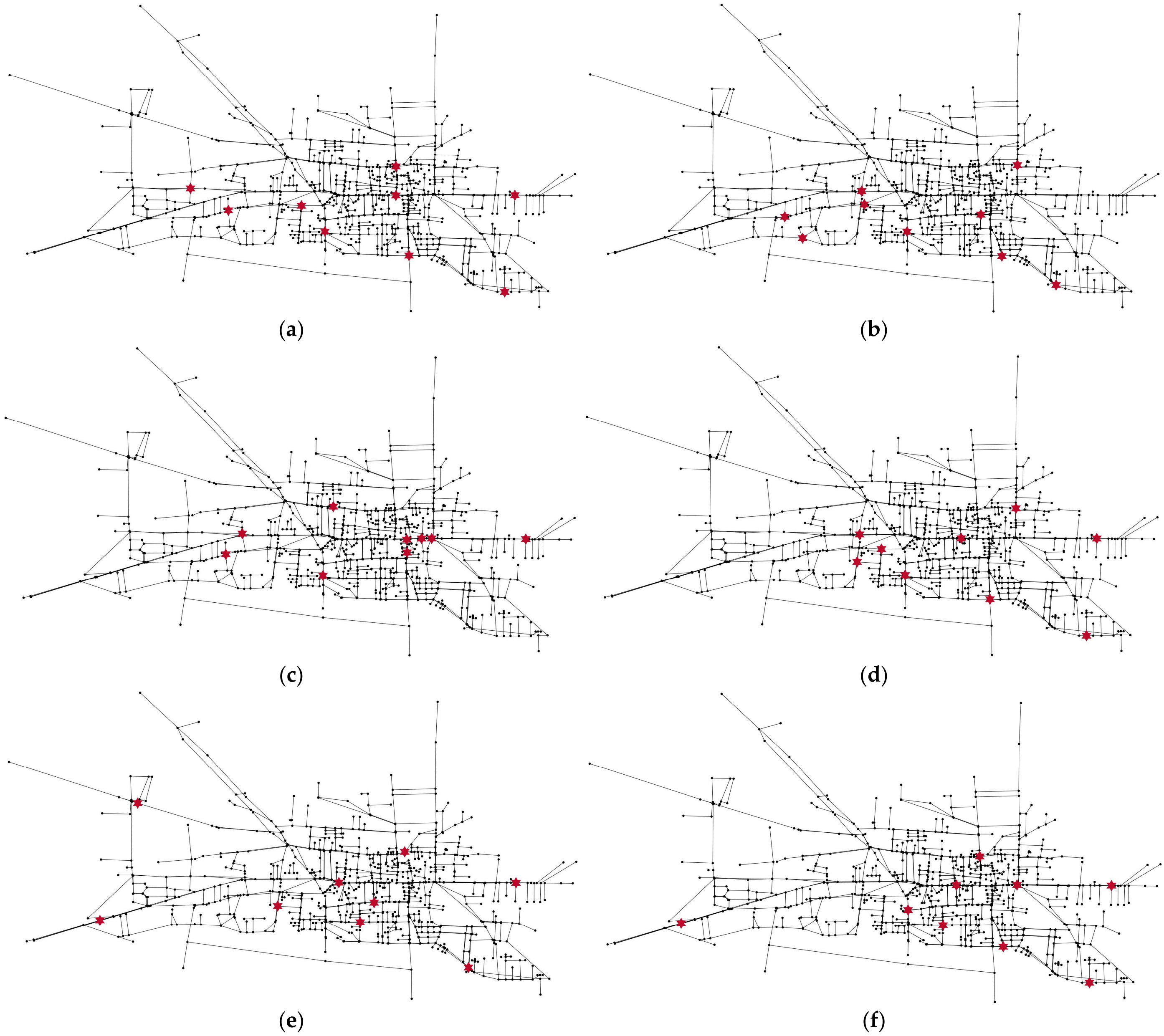
(**a**)
(**b**)
(**c**)
(**d**)
(**e**)
(**f**)

Figure 1. Sensor placement for (**a**) no weight, (**b**) capacity, (**c**) inverse of capacity, (**d**) diameter, (**e**) relative length and (**f**) inverse of length.

Observing Table 1, it is evident that the approach utilizing the relative showed the best results in terms of N_{eu} (both mean and maximum) and DP. This superiority can be attributed to the placement of sensors in the nodes connecting the longest pipes, which supply water to a significant portion of the population. Conversely, weights based on the capacity and inverse of pipe length yielded superior performance in terms of t_d. This can be attributed to the fact that pipes with short lengths and high diameters are characterized by lower hydraulic resistance, facilitating rapid water flow through the system. Although the unweighted approach did not surpass weighted alternatives, it still yielded effective results across all evaluated metrics.

Table 1. Number of exposed users mean (N_{eu_mean}), maximum (N_{eu_max}), DP, detection time mean (t_{d_mean}), maximum (t_{d_max}) computed for the different approaches. Best results are underlined.

	N_{eu_mean} **(%)**	N_{eu_max} **(%)**	DP **(%)**	t_{d_mean} **(min)**	t_{d_max} **(min)**
No weight	1.260	12.917	24	28	418
Capacity	1.736	26.206	20	29	243
Inverse of capacity	1.779	17.158	22	31	418
Diameter	0.979	11.981	26	28	382
Relative length	0.977	8.352	28	25	393
Inverse of length	1.395	14.512	23	23	388

4. Conclusions

This study presents a weighted topological approach for identifying optimal sensor locations within WDN. Various weighting schemes were evaluated, revealing that no single weight consistently outperformed others across all metrics. Consequently, the trade-off in selecting the most suitable weight may vary depending on the specific objectives of the water utility and network characteristics. However, $w_{RL,st}$ showed the best results for three out of five of the metrics used for the testing phase. Importantly, all proposed weighting methods are based on the physical characteristics of the network, enabling straightforward calculations with low computational costs. Despite this simplicity, the approach yields promising results in terms of mitigating contamination risks. Indeed, these sensor systems were able to ensure a limited mean number of exposed users (1–1.7%) in the case of simulated contaminations. Future research will focus on implementing optimization techniques for comparison reasons and to further enhance the effectiveness of the proposed approach. Additionally, these methodologies will be validated across networks of different sizes to confirm the robustness and efficiency of the weighted topological approach.

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