

Graph-Based Warm Solutions for Optimal Resilience Enhancement of Water Distribution Networks [†]

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Abstract: This study introduces an efficient graph-based approach for optimal resilience enhancement of existing water distribution networks through the re-sizing of specific pipes. It utilizes modified graph metrics to track the spatial failure propagation resulting from pipe (edge) failures. This leads to identifying pipes (edges) that are more vulnerable to the failure of others, making them suitable candidates for re-sizing. These selected edges undergo re-sizing using a graph-based design approach, generating diverse graph-based solutions. These solutions later serve as warm solutions for the initial population of evolutionary optimization to speed up convergence. Tested on two networks, this approach outperforms traditional optimization (with random initial populations), increasing computational efficiency by over 90%.

Keywords: complex network theory; pipe re-sizing; search space reduction



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1. Introduction

Enhancing the resilience of water distribution networks (WDNs) is crucial for safeguarding the well-being of societies in the face of disruptions. Among the diverse strategies applied for resilience enhancement in existing networks, the prevalent practice of pipe re-sizing stands out as a common and challenging task [1]. Traditionally, pipe re-sizing can be formulated as an optimization problem, where hydraulic-based evolutionary algorithms are employed to systematically search for optimal solutions (i.e., cost-efficient versus resilient). However, these algorithms face computational inefficiency due to the extensive search space size, particularly in large-scale systems [1]. Therefore, it is crucial to incorporate techniques that provide enhanced computational performance to improve the computational efficiency of resilience enhancement tasks. In this context, graph-based approaches emerge as an intriguing option, given their capability for rapid processing and minimal data requirements for WDN analysis [2,3]. However, their application for resilience analysis has often relied on conventional and elementary graph metrics that fail to capture the crucial aspects of WDN hydraulics [4,5].

Recently, researchers have employed tailored graph metrics for resilience enhancement purposes, aiming to more accurately represent hydraulic characteristics [1]. However, the literature still lacks a hydraulically informed graph-based approach that can be employed individually to generate various (near-optimal) solutions for pipe re-sizing. Such an approach has the potential to act as a surrogate for conventional evolutionary optimization problems or as an effective starting point in evolutionary optimizations for search space reduction. This study, as a part of our RESIST project, aims to fill this gap by proposing an efficient graph-based approach that can, firstly, provide a wide range of solutions

for resilience enhancement through pipe re-sizing without using any hydraulic solvers. Secondly, it aims to utilize these re-designs as warm solutions for the initial population of a hydraulic-based evolutionary optimization, thus achieving accurate and optimal solutions while addressing the challenges of computational inefficiency. The proposed approach is validated by comparing its results with those derived from traditional optimization (with random initial populations).

2. Methodology

The proposed methodology consists of three sub-chapters. Section 2.1 involves explaining the graph-based approach and obtaining graph-based solutions. Section 2.2 focuses on evolutionary optimization, and Section 2.3 introduces the case studies.

2.1. Graph-Based Solutions (GS)

Our proposed approach systematically removes each pipe (edge) from the WDN graph and utilizes modified metrics to analyze flow redistribution across alternative paths. It assesses whether these paths (edges) have adequate capacity to accommodate this redistribution. If not, they are identified as suitable candidates for resilience enhancement and are re-sized using a graph-based approach. The methodology for obtaining GS consists of four steps. Firstly, the mathematical graph of WDN is created, and the tailored graph measure called *demand edge betweenness centrality* EBC^Q [6] is calculated for every edge e as an estimation of water flow (Equation (1)), denoted as $EBC_D^Q(k)_{normal}$. EBC^Q is capable of identifying the shortest path (SP) linking a source node S and each demand node i , incorporating the respective demand Q_i of each node into the EBC^Q values associated with $SP_{S,i}$. The EBC^Q is calculated with the dynamic weight of length divided by diameter [7] to replicate the hydraulic flow regime and the effects of friction losses.

$$EBC^Q(k) = \sum_{i \in \text{demand nodes}} SP_{S,i}(k) \cdot Q_i \quad (1)$$

Secondly, an edge n whose removal (failure) does not disconnect the network graph from the source is removed (mimicking pipe failure). Following this, EBC^Q for every remaining edge k is re-calculated and called $EBC_D^Q(k)_{abnormal}$. The impact of this edge removal on every edge k is then called $gf_{k,n}$, calculated using Equation (2):

$$gf_{k,n} = \begin{cases} \frac{C_{ex}(k)_n - C_{max}(k)}{\delta(k)}, & C_{ex}(k)_n > C_{max}(k) \\ 0, & C_{ex}(k)_n \leq C_{max}(k) \end{cases} \quad (2)$$

where $C_{ex}(k)_n$ represents the disparity between $EBC_D^Q(k)_{abnormal}$ and $EBC_D^Q(k)_{normal}$ due to the removal of edge n in (L/s), which can be interpreted as an additional load on edge k . $C_{max}(k)$ is the maximum capacity of edge k in (L/s), calculated based on the maximum acceptable velocity (e.g., 3.5 m/s). In addition, $\delta(k)$ is the overloaded factor calculated by $\delta(k) = V_{max} / V(k)_{opt}$, where $V(k)_{opt}$ denotes the optimal velocity obtained from the recommended values from the literature [8].

Thirdly, the procedure outlined in step two is iterated by individually removing each edge n . Subsequently, the overloaded magnitude for each edge k is calculated by $OM(k) = \sum_{\substack{n=1 \\ (n \neq k)}}^{\#pipes} gf_{k,n}$ (L/s). Then, the edge k is deemed a candidate for re-sizing when its $OM > 0$.

Fourthly, the selected candidates are then re-sized using the graph-based design [6], where EBC^Q and OM are utilized to represent water flow in the volumetric flow equation to calculate a new diameter $D(k)_{new}$ using Equation (3). Accordingly, V_{design} , as design velocity can be adjusted in 0.01 m/s increments from 0.5 to 2.5 m/s, leading to 201 design solutions. Following this, the graphs associated with each solution undergo conversion

into EPANET files to assess their hydraulic-based resilience, enabling comparison with optimization results.

$$D(k)_{new} = \left\lceil \sqrt{\frac{4}{\pi} \cdot \frac{EBC_D^Q(k)_{normal} + OM(k)}{V_{design}}} \right\rceil \text{ with } D_{new} > D_{existing} \quad (3)$$

2.2. Hydraulic-Based Evolutionary Optimization

The optimization strategy employed for enhancing resilience through pipe re-sizing was adapted from Hajibabaei et al. [5]. An evolutionary optimization was conducted utilizing a modified version of NSGA-II [9] for pipe re-sizing, considering two conflicting objectives. The first objective seeks to minimize the cost of replacing the pipes, considering factors such as diameter, length, and road type. The second objective aims to minimize the average hydraulic failure magnitude (HFM_{avg}), representing the average percentage of unfulfilled demand in a WDN when pipes fail individually (i.e., single pipe failure). For further details regarding the optimization and HFM_{avg} , please refer to [5].

2.3. Case Studies

Two alpine WDNs in Austria are chosen to assess the proposed methodology. The first network is relatively small, comprising 268 pipes and 242 nodes, while the second network is considerably larger, with 4021 pipes and 3558 nodes. The graph-based approach is applied to both case studies, yielding graph-based solutions (GS). GS designs are then utilized as warm solutions for the initial population of hydraulic-based optimization, resulting in a Pareto front known as graph-based warm solutions (GWS). To validate the findings, hydraulic-based optimization (using random initial populations) is also conducted, referred to as OPT. However, due to the extensive search space required for resilience enhancement in the large WDN, OPT is only performed for the small network. Further details on the WDNs and their optimization parameters can be found in [5].

3. Results and Discussion

Figure 1 shows the obtained solutions for the resilience enhancement of the WDNs. In this figure, each solution's resilience enhancement is calculated as $(HFM_{(avg)existing\ WDN} - HFM_{(avg)_{new\ solution}}) / HFM_{(avg)existing\ WDN}$. In addition, critical pipes indicate the number of pipes in each solution with $HFM \geq 1\%$.

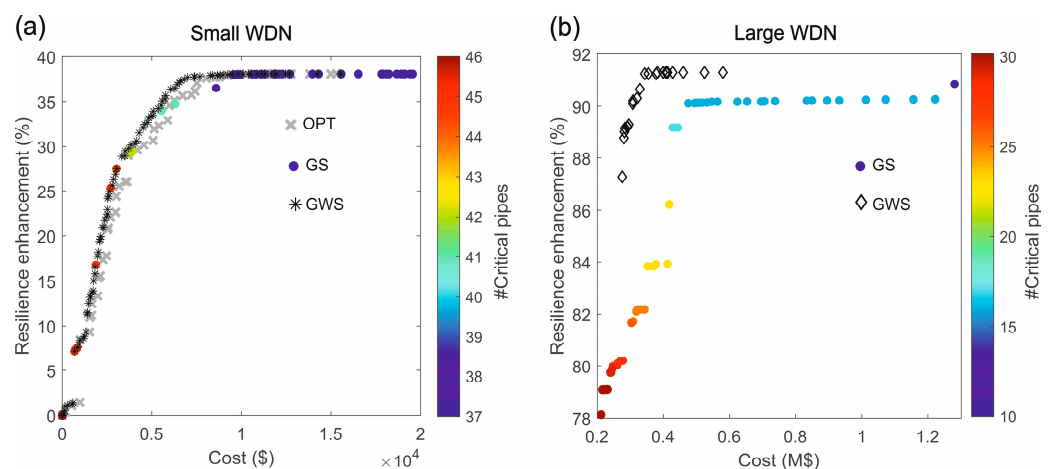


Figure 1. Resilience enhancement solutions based on OPT: hydraulic-based optimization with cold initial populations; GS: graph-based solutions; and GWS: graph-based warm solutions integrated with optimization for (a) small WDN and (b) large WDN.

Figure 1a shows that applying OPT (with random initial populations) to small WDNs can enhance resilience by up to 38%, achieved after 53,600,000 function evaluations ($268 \text{ pipes} \times 100 \text{ population} \times 2000 \text{ generations}$), requiring 240 h (10 days) to converge. However, GS yields comparable results within just 10 min. Integrating GS with optimization (45 warm solutions with 55 random solutions) forms GWS that converged after only 140 generations, outperforming OPT and GS, particularly in the knee area of the Pareto front. GWS was obtained in only 17 h, reducing computational burdens by 93% compared to OPT. Furthermore, in Figure 1b, half of the warm solutions (due to the very intensive computational burden) were utilized and combined with optimization, which resulted in GWS after 2,250,000 evaluations over two weeks of simulation time. GWS enhances resilience by up to 91.3% and significantly outperforms GS. Notably, GS for the large WDN was obtained in just 1.5 h, making it suitable for rapid resilience enhancement tasks or enabling a more comprehensible analysis (e.g., deep uncertainty analysis).

4. Conclusions

GWS demonstrates promising outcomes compared to traditional optimization by converging solutions towards the global optimal Pareto front, increasing diversity, and significantly reducing computational efforts. GWS proves especially beneficial for optimal resilience enhancement in large-scale WDNs with thousands of pipes, overcoming the computational burdens associated with conventional evolutionary optimizations.

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References

1. Diao, K.; Berardi, L.; Laucelli, D.B.; Ulanicki, B.; Giustolisi, O. Topological and hydraulic metrics-based search space reduction for optimal re-sizing of water distribution networks. *J. Hydroinform.* **2022**, *24*, 610–621. [\[CrossRef\]](#)
2. Hajibabaei, M.; Hesarkazzazi, S.; Minaei, A.; Dastgir, A.; Sitzenfrei, R. Using complex network theory for missing data reconstruction in water distribution networks. *Sustain. Cities Soc.* **2024**, *101*, 105114. [\[CrossRef\]](#)
3. Di Nardo, A.; Di Natale, M.; Giudicianni, C.; Greco, R.; Santonastaso, G.F. Complex network and fractal theory for the assessment of water distribution network resilience to pipe failures. *Water Sci. Technol. Water Supply* **2018**, *18*, 767–777. [\[CrossRef\]](#)
4. Meng, F.; Fu, G.; Farmani, R.; Sweetapple, C.; Butler, D. Topological attributes of network resilience: A study in water distribution systems. *Water Res.* **2018**, *143*, 376–386. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Hajibabaei, M.; Yousefi, A.; Hesarkazzazi, S.; Minaei, A.; Jenewein, O.; Shahandashti, M.; Sitzenfrei, R. Resilience enhancement of water distribution networks under pipe failures: A hydraulically inspired complex network approach. *AQUA—Water Infrastruct. Ecosyst. Soc.* **2023**, *72*, 2358–2376. [\[CrossRef\]](#)
6. Sitzenfrei, R.; Wang, Q.; Kapelan, Z.; Savić, D. Using complex network analysis for optimization of water distribution networks. *Water Resour. Res.* **2020**, *56*, e2020WR027929. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Hajibabaei, M.; Hesarkazzazi, S.; Minaei, A.; Savić, D.; Sitzenfrei, R. Pareto-optimal design of water distribution networks: An improved graph theory-based approach. *J. Hydroinform.* **2023**, *25*, 1909–1926. [\[CrossRef\]](#)

8. Baur, A.; Fritsch, P.; Hoch, W.; Merkl, G.; Rautenberg, J.; Weiß, M.; Wricke, B. *Mutschmann/Stimmelmayer Taschenbuch der Wasserversorgung*; Springer: Berlin/Heidelberg, Germany, 2019; ISBN 3658232226.
9. Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [[CrossRef](#)]

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