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A graph-based approach for structural resilience assessment in the urban drainage network

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Abstract

This study addresses the significant challenge of conduit blockage in urban drainage networks (UDNs), commonly caused by sediment transfer during runoff. Such blockages can lead to flooding, even during low-intensity rainfall, thereby disrupting urban traffic and infrastructure. To tackle this issue, a novel approach proposed a topology-based approach that converts the urban drainage network into a graph-based model, enabling the identification of critical pipes for strategic interventions. By implementing modified graph theory metrics, flood volume, and total runoff were calculated for single pipe failure scenarios, facilitating the assessment of urban drainage network resilience. The methodology is validated through one real-case study, analysing return periods of one and two years and varying durations of 10, 30, and 60 minutes. Results demonstrate that the graph-based method exhibits a high degree of consistency with the established stormwater management model (SWMM), highlighting its potential as an effective tool for improving urban drainage resilience and mitigating conduit failure risks.

Highlights

- Sediment built up in urban drainage pipes can lead to significant flooding risks.
- Rapid assessment of pipe failure resilience supports effective stormwater management.
- A graph-based resilience index identifies key components of the drainage network.

Introduction

In urban drainage networks (UDNs), blockages caused by sediment deposits in conduits or the collapse of conduits during high-intensity rainfall can lead to urban flooding. Such flooding disrupts traffic and can trigger cascading failures in various urban infrastructures and the environment (Yazdi, 2018; Mugume et al., 2015). Consequently, a UDN must return to a safe condition promptly after any disruptions. For this reason, researchers have characterized structural resilience in urban drainage systems as the ability of a system to reduce both the intensity and duration of service interruptions throughout its expected lifespan, especially when encountering failures in the network's components (Mugume et al., 2015).

In previous studies, researchers frequently employ the Storm Water Management Model (SWMM) to calculate flood volumes and total runoff for resilience formula assessments. This model, developed by the United States Environmental Protection Agency, utilizes the Saint-Venant equations for one-dimensional flow modeling. For instance, Mugume et al. (2015) utilized the SWMM model for global resilience assessment, exploring various combinations of multiple pipes within urban drainage networks to evaluate resilience. Similarly, Mohammadiun et al. (2020) employed the SWMM model to

minimize flood volumes under scenarios of stochastic pipe blockage, representing structural resilience. Additionally, they considered rehabilitation costs as another objective in their study.

Furthermore, due to the time-consuming nature of running models for various pipe failure scenarios, some studies utilize alternative topological characteristics and graph theory methods to assess structural resilience. For example, Hajiamoosha et al. (2023) utilize a graph network of a UDN and assess its robustness during structural failures by analysing connectivity metrics and variations of these metrics in failure scenarios. Furthermore, Meijor et al. (2024) employed a framework called the Graph-Based Weakest Link Method (GBWM) to evaluate UDN resilience in bottleneck scenarios. They analyzed the relationships among several simple metrics, including node degree, connectivity, and betweenness centrality, along with modified versions of topological metrics that consider both the capacity and gradient of the pipes for the resilience assessment of the network.

Using a graph theory model can be faster and requires fewer physical data for a UDN. However, relying only on basic graph metrics may not be sufficient for a thorough resilience assessment of a UDN. To fill this gap in the graph-based method, this research proposes modified hydraulically informed topology metrics, calculating the flow in each pipe similar to the SWMM model, and ultimately determining the structural resilience of the UDN in a single pipe failure scenario.

Methodology

The graph-based structural resilience assessment method consists of two main steps. In the first step, the inflow of each pipe is calculated based on runoff edges using a centrality metric as a modified graph theory metric. In the second step, the resilience of the urban drainage network is determined. The complete sequence of these steps is illustrated in (Figure 1)

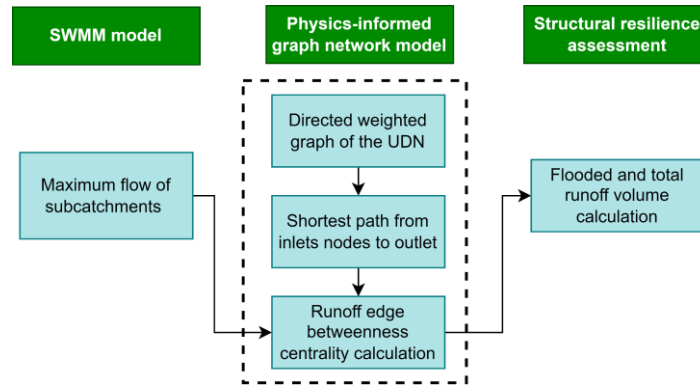


Figure 1. steps of graph-based structural resilience assessment

Physic-informed model of the UDN

Previous studies, including Hesarkazzazi et al. (2022) and Dastgir et al. (2024), used modified graph theory metrics to assess pipe inflow and flood volume. They estimated the flow path from nodes to the outfall of the UDN by calculating the weighted shortest path $\sigma_{i,j}$ in the graph network, ultimately determining flow distribution in UDN pipes (Dijkstra, 2022). This thesis also introduces runoff edge betweenness centrality (REBC) to represent the hydraulic behaviour of a UDN. REBC for pipe e is derived from the maximum flow of subcatchments using the SWMM hydrologic model. The REBC is calculated for all inlet nodes j and the outfall node i , as shown in (Equation 1).

$$REBC(e) = \sum_{i,j} \sigma_{i,j}(e) \times \max runoff f_j [0 \sum_{j \in D} \max runoff f_j] \quad (1)$$

Structural resilience assessment of the UDN

The graph-based structural resilience of a UDN in the event of pipe failure during design rainfall is derived from (Equation 2 and Equation 3). The new resilience formula proposed in this research is based on the estimated flow variation graph of the connected pipe to outfall and failed pipe, as illustrated in (Equation 3) and (Figure 2). To enhance the accuracy of the graph-based resilience model, the volume of water stored in the pipe after flooding is subtracted from the total flood volume

$$Res = 1 - \frac{\text{flood volume}}{\text{Total runoff volume}} \quad (2)$$

$$Res = 1 - \frac{\text{Area of } CDE - \text{stored water}}{\text{Area of } ABC} \quad (3)$$

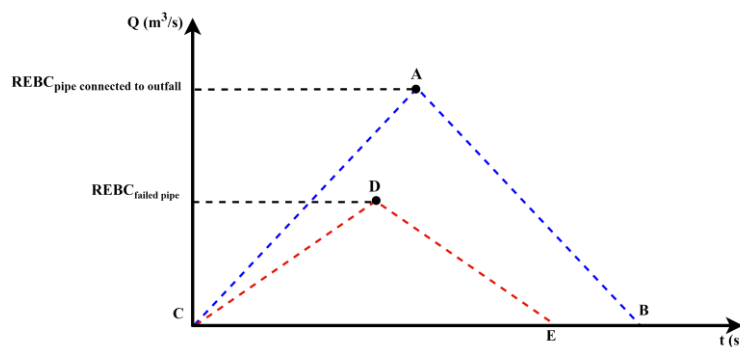


Figure 2. Estimated flow variation of failed and connected pipe to outfall

The volume of water stored in the pipe due to gravitational flow cannot drain from points of lower elevation than the flooded manhole; instead, it remains trapped within the conduit. The amount of stored water can be calculated using takes into account the pipe's geometry and the topology of the network.

Case study

This methodology is conducted in a real case study located in alpine city. This case study comprises 372 conduits and 372 manholes along with one outfall and is illustrated in Figure 1.



Figure 3. layout of the real case study in the alpine cities area

Results and discussion

The resilience values obtained through the graph theory method were compared with those derived from the SWMM model, revealing a high level of consistency between the two approaches. The resilience values for various scenarios are presented in (Figure 4). Furthermore, the correlation between these two models is summarized in (Table 1). As illustrated in (Figure 4), rainfall events of shorter duration demonstrate greater accuracy compared to longer durations. Overall, for all data points across one- and two-year return periods, as well as for durations of 10, 30, and 60 minutes across six rainfall scenarios, the model exhibits significantly high accuracy based on the six assessment indicators.

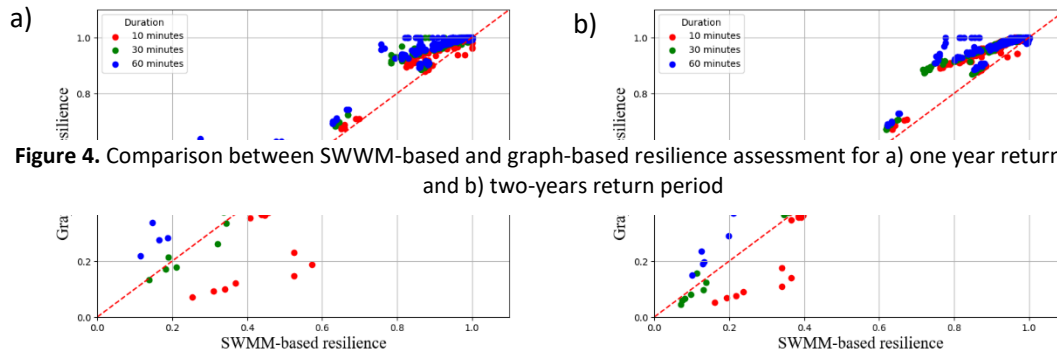


Figure 4. Comparison between SWMM-based and graph-based resilience assessment for a) one year return period and b) two-years return period

Table 1. Different model accuracy assessment

| | |
|--|---------------|
| Pearson correlation coefficient | 0.9687 |
| concordance correlation coefficient | 0.9505 |
| R2Score | 0.9005 |
| Mean squared error | 0.0030 |
| Mean absolute error | 0.0380 |
| Spearman correlation coefficient | 0.8782 |

Conclusions and future work

In this study, the resilience of the urban drainage network in an alpine city is computed using a novel method developed through graph theory. This approach is faster than the SWMM model and can serve as a suitable option for resilience enhancement methods in large networks that require significant computational resources. However, it is important to note that this method has only been applied to designed rainfall events. Its efficiency could greatly improve if applied to high-intensity rainfall scenarios, allowing for more comprehensive and robust resilience assessments. To achieve this, a more detailed, physics-informed graph is necessary to account for the capacity of pipes and the effects of pipe failures on downstream conduits.

Acknowledgement

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