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Flood Resilience Assessment of Urban Drainage Systems: A Graph Theory Perspective

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Abstract

In urban areas experiencing intense rainfall, inadequate drainage network capacity can lead to runoff flooding from manholes, resulting in urban floods and disruptions to various infrastructure, including road networks. Developing a fast and robust model is essential for addressing this functionality failure in urban drainage networks (UDNs) and enhancing resilience. This research introduces a novel method for calculating flood volume in urban drainage networks using the graph theory method. The graph-based approach proposes modified graph metrics to rout the runoff in conduits, enabling the identification of overflow conditions for accurate flood calculations. This methodology is applied in a real case study in an alpine city area, and the resilience values calculated for rainfall durations of 10, 15, 20, and 30 minutes, along with return periods of 1 to 100 years, demonstrate a strong consistency with results obtained from a stormwater management model (SWMM) utilizing dynamic wave methods for flow routing.

Highlights

- Fast calculation of pluvial flooding resilience can be useful for real-time flood management.
- Physics-informed graph network can mimic the hydraulic model behaviour.
- A graph-based resilience index identifies key components of the drainage network.

Introduction

Global warming and urbanization have notably heightened the frequency and severity of urban flooding, leading to significant damage to infrastructure like drainage networks and roadways. As a result, extensive research has been conducted to evaluate flooding impacts and develop effective mitigation strategies (Prashar et al., 2023). Recent studies on flood management have increasingly focused on urban resilience, which is defined as the capacity of communities, cities, or nations to withstand, absorb, and recover from shocks such as extreme floods, and adapt effectively to changing conditions (UNESCO, 2013).

Flood modeling and mapping are essential for accurately assessing flood resilience, enabling researchers to track flood locations and assess their impacts. Various physical and data-driven models have been employed for flood analysis, with one-dimensional (1D) models offering speed and simplicity, particularly for UDN, while two-dimensional (2D) models provide more accurate inundation mapping but require more time. Data-driven models, which do not depend on extensive physical data of infrastructure, allow for quicker assessments (Qi et al., 2023).

In addition to these methods, graph theory-based models offer a simplified approach that requires less detailed information, typically relying on fundamental parameters such as slope, diameter, and pipe length. This efficiency enables effective analysis while capturing essential geometric relationships in flood modeling (Xiaoyu et al., 2023). Some studies are also exploring hybrid data-driven models that integrate physically guided equations with graph neural network techniques, enhancing predictive capabilities while retaining the physical relevance of the modeling process (Zhang et al., 2024).

In summary, a flood resilience assessment model that minimizes reliance on detailed data and can integrate with other infrastructure models represents an optimal solution for evaluating urban flood resilience. As a result, this research proposes a physics-informed graph network that replicates the hydraulic behavior of the drainage network. This model is faster than traditional hydraulic models and does not rely on extensive data, unlike pure data-driven methods.

Methodology

The sequence for assessing flood resilience in urban drainage networks (UDN) is illustrated in (Figure 1). Initially, the flow of conduits is determined using specific graph network metrics. Ultimately, the flood resilience value is established based on the analysis of the symmetrical flow variation graph.

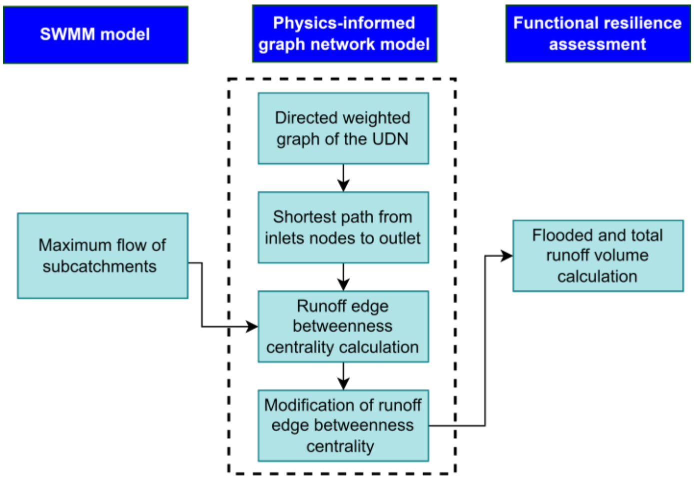

Figure 1. Steps of functional resilience assessment

Physics-informed graph network

In this research, the flow of conduits is determined based on a modified graph metric known as runoff edge betweenness centrality (REBC), which is used by researchers such as Hesarkazzazi et al. (2022) and Dastgir et al. (2024). In REBC calculation the weighted shortest path $\sigma_{i,j}$ from inlet nodes *j* to outlet nodes *i* is first computed using Dijkstra's method to identify the flow path (Dijkstra, 2022). Next, for each conduit c, the sum of the $max\ runoff_j$ from subcatchments connected to inlet nodes *i* along the shortest paths through conduit *c* is calculated as REBC according to (Equation1).

$$REBC(e) = \sum_{i,j} \sigma_{i,j}(e) \times max\ runoff_j; \quad Range\ of\ REBC : [0, \sum_{j \in D} max\ runoff_j] \qquad (1)$$

To address the drawbacks associated with the capacity of pipes during high-intensity rainfall, a modified version of REBC is developed. The value of this metric is decreased when the flow is higher than the maximum capacity of the pipe. After the calculation of REBC, this modification is applied starting from the furthest node from the outfall and proceeding to the nearest node.

Flood resilience index

Ultimately, the graph-based flood resilience for the UDN was determined using the adjusted *REBC* metrics that indicated the maximum flow capacity of the conduits. This value was derived from estimating flow changes over time in the conduits linked to the UDN's outfalls. The flow variation is depicted as a symmetrical graph in (Figure 2), and based on this graph (Equation 2) and (Equation 3) represents functional resilience during periods of intense rainfall. Furthermore, as shown in the figure, $REBC_{base}$ denotes the threshold level of REBC where a distinction between the REBC and modified REBC is identified, indicating that a flood event is occurring within the system. This analysis utilized the REBC value associated with the design rainfall to define $REBC_{base}$.

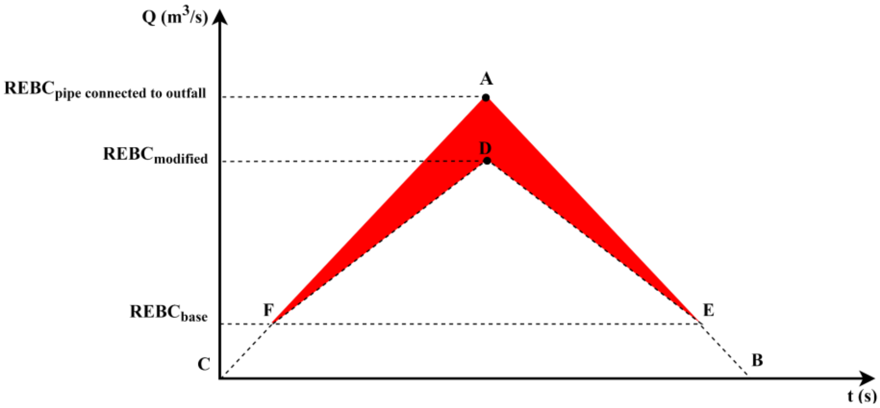

Figure 2. Flow variation of pipe connected to the outfall

$$Functional\ Resilience_{Graph-based} = 1 - \frac{Area\ of\ AEDF}{Area\ of\ ABC} \quad (2)$$

$$Functional\ Resilience_{Graph-based} = 1 - \frac{\left(REBC - REBC_{modified}\right) * \left(REBC - REBC_{base}\right)}{REBC^2} \quad (3)$$

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 3).

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

Results and discussion

The graph-based resilience assessment was conducted for twelve rainfall scenarios, including durations of 10, 15, 20, and 30 minutes, as well as return periods of 1 to 100 years. The results obtained from the graph-based method were compared with those from the Storm Water Management Model (SWMM), as shown in Figure 4. The graph-based resilience assessment demonstrated a strong consistency with the SWMM model across various rainfall events, and the accuracy of the model is detailed in Table 1. As can be seen in (Figure 4) rainfall events with lower duration have more consistency with the SWMM model and the graph-based model can be a good option for the low-duration rainfall events with simple distribution.

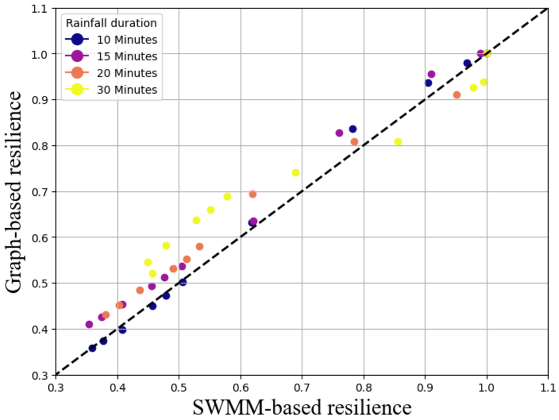

Figure 4. graph-based and SWMM-based resilience values

Table 1. Accuracy of graph-based model

Pearson correlation coefficient	0.9853
Concordance correlation coefficient	0.9743
R^2 score	0.9512
Mean squared error	0.0026
Mean absolute error	0.0400
Spearman correlation coefficient	0.9750

Conclusions and future work

A graph-based resilience assessment method has been developed to accurately calculate the value of flood resilience for various rainfall events. This method is effective for high-intensity rainfall, but it's essential to note that this research only considers the flooded volume of the drainage network. However, the drainage network has a significant interaction with runoff from streets, and a substantial amount of water is not captured by the drainage network. Therefore, future work should focus on integrating the interaction between road networks and drainage networks to conduct a comprehensive flood resilience assessment.

Acknowledgment

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