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# Graph-theoretical representation of impact propagation in urban stormwater networks

Mohsen Hajibabaei <sup>1</sup>  <https://orcid.org/0000-0002-0047-9715>,  
 Mohammad Rajabi <sup>1</sup>  <https://orcid.org/0009-0004-5375-3978>, Guangtao Fu <sup>2</sup>  <https://orcid.org/0000-0003-1045-9125>,  
 David Butler <sup>2</sup>, & Robert Sitzenfrei <sup>1,\*</sup>  <https://orcid.org/0000-0003-1093-6040>

<sup>1</sup>Unit of Environmental Engineering, Department of Infrastructure Engineering, University of Innsbruck, Innsbruck, Austria

<sup>2</sup>Centre for Water Systems, University of Exeter, Exeter, United Kingdom

\*Corresponding author email: [Robert.Sitzenfrei@uibk.ac.at](mailto:Robert.Sitzenfrei@uibk.ac.at)

## Abstract

Any disruptions in urban stormwater networks (USNs), such as sewer or manhole failures, can propagate impacts beyond their immediate spatial location (e.g., upstream or downstream). However, determining where and to what extent these impacts propagate is often challenging due to the complex hydraulic behaviour of such systems. This study introduces a modelling framework using graph theory to represent the consequences of failure propagation. The framework quantifies the impacts of junction failures on other elements of USNs through hydrodynamic modelling. These impacts are then decoupled from the physical USN topology and represented as a directed and weighted graph, termed "impact network", where edge weights capture the actual consequences beyond the failure's point of origin. The application of the proposed framework was demonstrated through systematic investigations of a real-world case study. This analysis led to the identification of the most influential nodes driving impact propagation and the most affected nodes exposed to the propagated impacts. Furthermore, the spatial interconnections between the impact network and critical urban locations were analysed, enabling the prioritisation of nodes of strategic importance.

## Highlights

- Integration of hydrodynamic modelling and graph theory for failure propagation analysis.
- Representation of failure impacts beyond their spatial origin using directed graphs.
- Analysis of spatial interconnections between impact propagations and critical urban areas.

## Introduction

Urban stormwater networks (USNs) are critical infrastructure designed to protect urban areas from pluvial flooding. These systems, however, are exposed to various natural and human-induced threats that can result in different failures, such as structural (e.g., due to sewer blockages) and functional (e.g., due to extreme rainfall events) (Hajibabaei et al., 2025; Mugume et al., 2015). These challenges highlight the need to build resilience in USNs. Resilience, in this context, refers to the ability of a USN to minimise the magnitude and/or duration of failures under extreme conditions or disruptive events (Butler et al., 2014). However, one of the important aspects of assessing USN resilience from a broader perspective is understanding how failures, whether caused by extreme rainfall, urbanisation, or blockages, propagate within these networks and affect critical locations beyond their point of origin. While existing studies have explored failure consequences at a global system level using resilience or hydraulic performance indicators (Mugume et al., 2015; Wang et al., 2021), they often lack a

systematic approach to characterising failure propagation impacts. To address this gap, this study introduces a graph-theoretical method to represent and evaluate failure propagations, providing a new perspective on the resilience assessment of USNs.

## Methodology

### Representation of impact propagation

This study focuses on representing the propagation of impacts caused by single-node (manhole) failures. In this context, a node failure is modelled using the Stormwater Management Model (SWMM v5.1) (Rossman, 2010) by significantly increasing the Manning's roughness coefficient of all links connected to the node to a high value ( $n=100(-)$ ) (Mugume et al., 2015). This increase in roughness effectively restricts the conveyance of flows in the connected links, simulating the complete node failure. In this situation, the consequences can be categorised into two groups: (1) the local impact at the node itself, quantified by the flood volume at the failed node, and (2) the propagation impact, quantified as the flood volume observed at other nodes. The aim is to detach these impacts from the network topology while accounting for the actual failure consequences (e.g., flood volume) on other nodes using a directed and weighted graph. It is important to note that all nodes are assumed to be susceptible to failure. To better explain the procedure, an illustrative USN is shown in Figure 1a. For example, the impact of failure of node 1 on the entire USN is analysed in Figure 1b and is systematically represented as a directed and weighted graph. The local impact (i.e., flood volume at the failed node) is mapped on the node itself. Further, in that graph, the weight of the edge between nodes 1 and 3 is proportional to the flood volume at node 3 caused by the failure of node 1, as determined by SWMM. A similar procedure is applied to other nodes, with the propagated and local impacts represented as "element impacts" in Figure 1b. These element impacts are then combined into an "impact network" (Figure 1c), collectively representing the combined spatial consequences of all failure scenarios and their local impacts. The created impact network serves as the foundation for systematic graph analyses, providing insights into failure consequences and their propagation patterns.

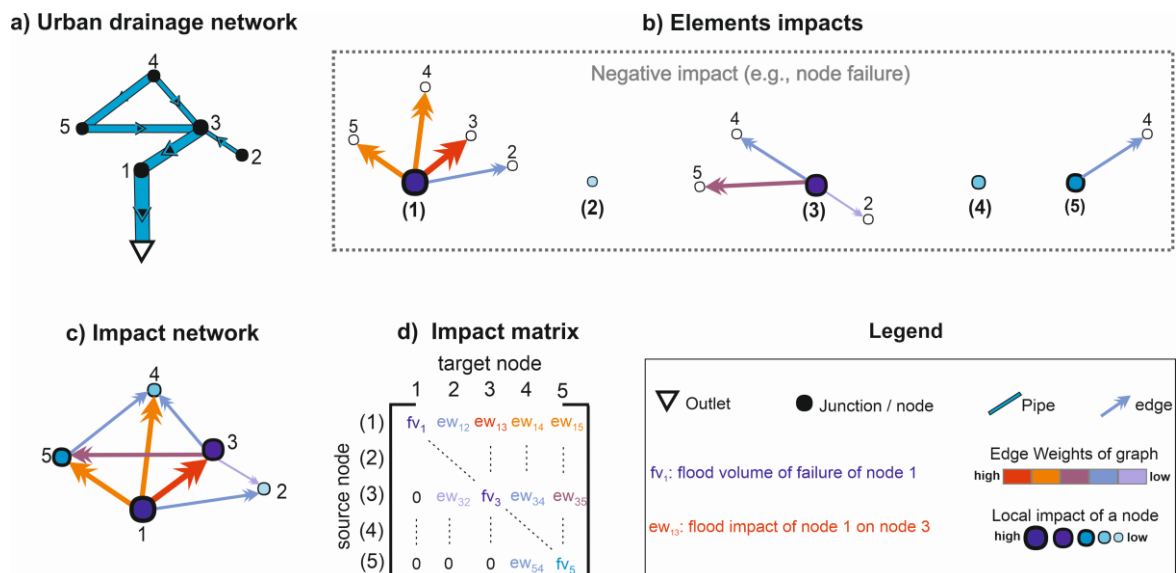


Figure 1. Schematic example for representing impact propagation in USNs using

## Graph characteristics of impact network

Different graph metrics can be applied to conduct a systematic analysis of the impact network. This study focuses on three key metrics for node criticality analysis to demonstrate one of the applications of the proposed approach. The first graph metric is the node outdegree ( $OUT_i$ ), which indicates the number of outgoing edges from node  $i$ . For example, the node outdegree of node 1 in Figure 1c is 4 ( $OUT_1 = 4$ ). Outdegree can serve as an indicator in the impact network to identify the most influential nodes, meaning nodes whose failures are more often spatially propagate impacts compared to others. The second graph metric is the node indegree ( $IN_i$ ), which represents the number of incoming edges to node  $i$  (e.g., in Figure 1c,  $IN_5 = 2$ ). This metric highlights the most affected nodes, specifically those more frequently exposed to the impacts of other node failures. In addition to indegree, another measure for identifying the most affected nodes is node weight ( $W_i$ ). In this context, the node weight of each node  $i$  is calculated as  $W_i = k_i^{IN}$ , where  $k_i^{IN}$  represents the sum of the incoming edge weights to node  $i$  ( $m^3$ ), which is proportional to the total flood volume at node  $i$ . Unlike node indegree ( $IN_i$ ), which measures how often a node is affected by the failure of others, node weight ( $W_i$ ) reflects the magnitude of the incoming impacts. These metrics are applied to the impact network of a real-world USN, enabling the identification and ranking of important nodes.

## Case study

An Alpine municipality in Austria was selected as the case study. Figure 2a illustrates the layout of the USN in this city. The USN comprises 372 nodes and 371 sewers with 12 diameter classes. Node failures were simulated under a 2-year block rain event to construct the impact network. In addition to the USN, the land classification of the investigated area (Figure 2b) was utilised to explore the spatial interconnections between the USN's impact network and various urban areas.

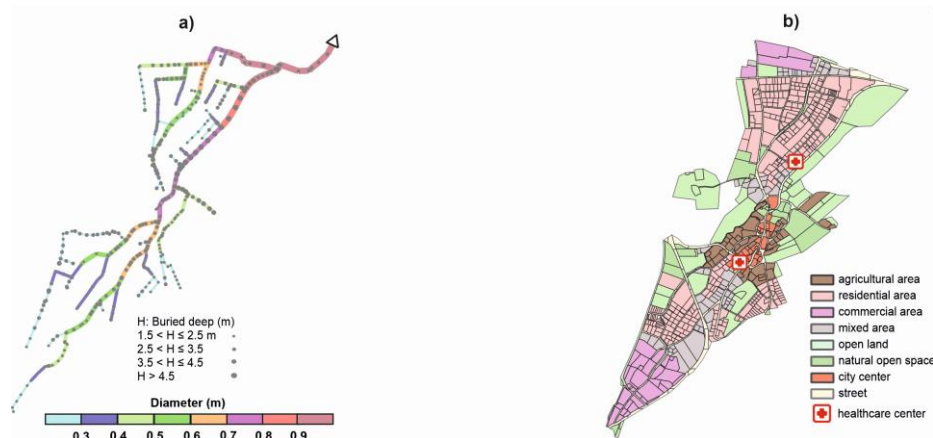
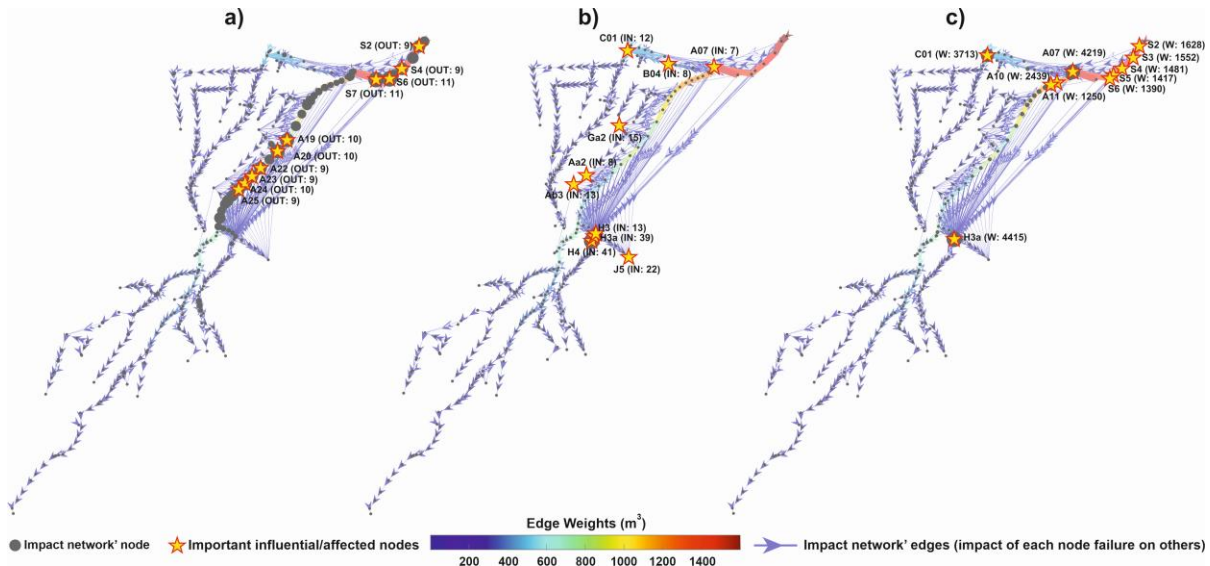


Figure 2. Case study: a) layout of the USN; b) land classification of the investigated area.

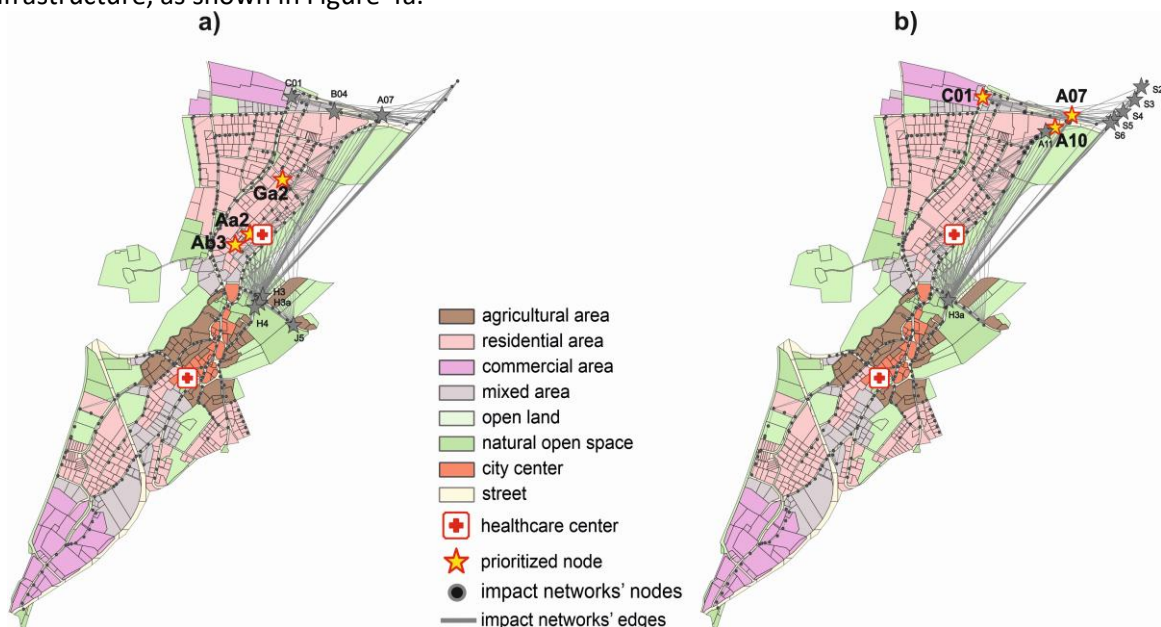
## Results and discussion

Figure 3 illustrates the impact network of the investigated USN, where edge colours and thickness are proportional to the edge weights, and node sizes correspond to node criticality, either in terms of being influential or affected. In Figure 3a, the top 10 influential nodes, those with the highest outdegree, are marked in yellow. These nodes require special attention from water utilities as they more frequently propagate negative impacts beyond their original spatial locations compared to other nodes.



**Figure 3.** Impact network of the investigated USN. a) Top 10 influential nodes based on outdegree (OUT); b) Top 10 affected nodes based on indegree (IN); c) Top 10 affected nodes based on node weight (W).

On the other hand, Figures 3b and 3c highlight the top 10 affected nodes based on indegree and node weight metrics, respectively. As shown, these affected nodes, such as H3a, with high indegree and node weight, are highly exposed to propagated impacts from others. Therefore, it is crucial to investigate the spatial interconnections between these affected nodes and urban areas to prioritise those located in critical regions. This spatial analysis, shown in Figure 4, identifies and highlights the top 3 prioritised nodes. The prioritisation was conducted based on the urban area's critical infrastructure and population density. For example, although H3a in Figures 3b and 3c exhibits a high indegree and node weight, it is located in agricultural and open land areas (see Figure 4), making it less critical for prioritisation. In contrast, a node like Aa2, despite not having the highest indegree according to Figure 3b, is prioritised due to its interconnection to a healthcare centre, a critical urban infrastructure, as shown in Figure 4a.



**Figure 4.** Spatial interconnection between the affected nodes and urban areas. a) Top 3 prioritised nodes based on indegree (IN) and land classification; b) Top 3 prioritised nodes based on node weight (W) and land classifications.

## Conclusions and future work

The proposed graph-based approach facilitates the modelling of impact propagations from disruptions in USNs beyond their spatial location, providing valuable insights into the complex behaviours of USNs. In this study, the impacts were quantified solely based on flood volume; however, future work will incorporate additional criteria, such as flood duration, and consider more complex USNs. Future research will also investigate different levels of blockages to better understand their effects on failure propagation and network resilience.

## Acknowledgement

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