Identification of critical locations for introducing redundancy in stormwater networks

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Highlights

- With complex network analysis, modelling stormwater networks are computationally efficient.
- Identified locations for additional redundancy enables a better flow distribution (less flooding).
- Within a reasonable budget, building a tree-loop integrated structure is hydraulically promising.

Introduction

Exacerbated by ongoing phenomena such as climate change and urbanization, urban surface flooding has imposed numerous negative impacts on many cities worldwide (Wang et al. 2018). Urban drainage systems (UDSs) are an integral and vital component of cities, the proper and reliable function of which can minimize the resulting flooding consequences under unexpected loading conditions. Incorporating resilience into UDSs is recognised as a valuable asset to achieve this goal (Butler et al. 2014). Resilience and reliable based solutions broadly fall into three categories: 1) mitigation, 2) coping and 3) adaption. Adaption measures include flexibility and redundancy, and the latter is enhanced by establishing components with similar functions to the systems e.g., adding centralized storage tanks or introducing parallel pipes or loops (Mugume et al. 2015). As the in-depth understanding of redundancy characteristics to minimize failure propagation through the system is still unclear (Butler et al. 2014), this study aims at identifying the sensitive locations for constructing loops in the storm sewer system. In the context of redundancy, the examples are rare. For instance, Zhang et al. studied the impact of branched and looped systems on the vulnerability of UDSs based on blockage scenarios (Zhang et al. 2017). Furthermore, the structures of different UDSs were evaluated in terms of increased rain events (Lee et al. 2018; Reyes-Silva, Helm, and Krebs 2019). However, a generic technique, starting with a grid-like structure (based on e.g., street network), with which inefficient redundancy (additional pipes) can be systematically eliminated, is still lacking. The main goal of this paper is, hence, to systematically address the redundancy characteristics of UDSs by developing an automated method using complex network analysis. This approach, consequently, enables to detect the critical locations in the network, through which peak runoff can be more efficiently discharged (better flow distribution).

Materials and Methods

Complex network analysis

UDSs can be described with graph theory. Such networks are composed of vertices i.e., manholes, storage units, outfalls and edges i.e., conduits, pumps and weirs. These networks (graphs) can be either (weighted) directed (representing flow direction) or (weighted) undirected. Weights can be assigned to pipes. A common weight for a pipe is the Euclidean distance. Analysis of the graph are then related to path lengths. However, by assigning different weights (e.g., related to hydraulics), also hydraulic characteristics can be analysed. In this study, edge betweenness centrality is also utilized, signifying how frequent an edge is part of the shortest path between source vertices (S), that is, inlet nodes, to only target vertices (T), that is, outlets(s). This edge betweenness centrality is denoted here as $EBC^{*}{}_{e}$, the equation of which is given by:

$$EBC^{*}{}_{e} = \sum_{S=1}^{N} \sum_{T=1}^{O} \frac{n_{ST}(e)}{n_{ST}} \tag{1}$$

Where $EBC^{*}{}_{e}$ is the edge betweenness centrality of edge e, $n_{ST}(e)$ is the number of shortest path between vertex S and T which passes through edge e. Additionally, O and N denote outlet(s), and nodes respectively.

Generation of stormwater structures (configurations)

We aim here at systematically eliminating the additional pipes. Such experiment is conducted numerous times with different sequences of pipes removed from a base layout to infer the optimal configuration (level of redundancy). Consequently, the critical locations at which constructing additional pipes can more efficiently distribute the flow through the system, are identified. Due to the strong correlation between street networks and urban water infrastructures, the base grid-like layout, can be also regarded as street networks (Mair et al. 2017). Initially, the base (looped) stormwater system is hydraulically designed. Afterwards, Equation (1) is applied to the network; and edges with $EBC^*{}_e$ values equal to zeros are then successively and randomly deleted. For the real-world demonstration case with initially 276 pipes and 237 nodes, this leads to 41 individual network configurations (from the 40-looped network (base) to the branched one). This procedure is repeated 80 times (3,280 networks were generated). In the current study, we investigate the effect of pipes elimination, resulting in non-preferential flow pathways. For that, the appropriate weights have to be assigned to the pipes in the graph. According to Manning's formula, volumetric flow rate [$\frac{m^3}{s}$] can be expressed in terms of networks' structural characteristics as $Diameter^{\frac{8}{3}} \times Slope^{\frac{1}{2}}$. In addition, length of the pipes is integrated into edge weights to gain a better understanding towards network's hydraulic properties and to implicitly include lengths-based pipe costs in the procedure. Hence, to determine preferential flow pathways through pipes, inverse values are used as edge weights; and correspondingly, $Edge\ weight_e = \frac{Length_e}{Diameter_e^{8/3} \times Slope_e^{1/2}}$ is considered and computed for all edges. The proposed edge weight can be interpreted as that shorter connections with higher capacities attract more flow.

Performance Assessment

Two assessment indicators: total construction costs and flood reliability (flooded volume and flooded nodes) are evaluated. Total costs presented by Maurer et al. (Maurer, Scheidegger, and Herlyn 2013) are utilized, which takes into account the average cover depth, diameter and lengths for each pipe section. The hydraulic performance is assessed with SWMM5. The performance indicator applied is expressed by flooding behaviour based on Euler II rain event and 6 different return periods. The original return periods considered are {2, 3, 5, 10, 20, 30, 50, 100 and 200} in years. The impact of urbanization (represented as increased return period for the assessment) is considered, achieved by incorporating, city growth rate and planning horizon associated with infrastructure's lifespan (Kleidorfer, Sitzenfrei, and Rauch 2014) by Equation 2 below:

$$RP^* = RP.\ (1+g)^{1.92t} \tag{2}$$

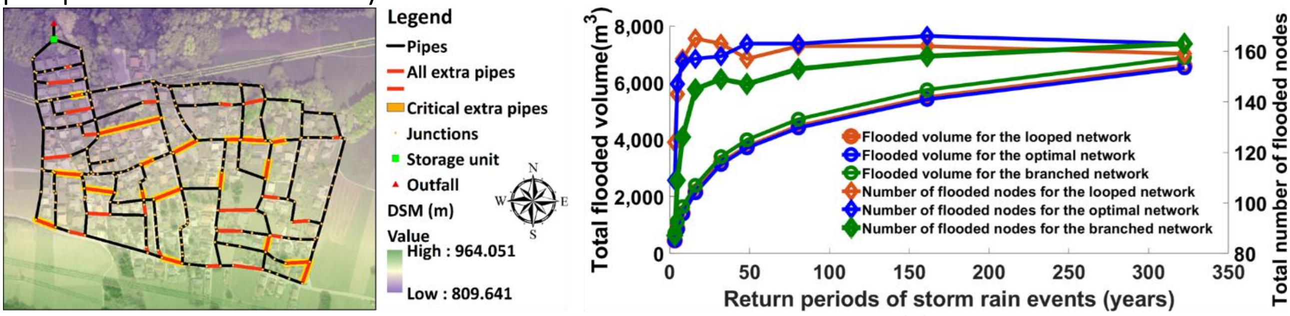
Where RP^* is increased as new return period (years), *RP* is original return period (years), *g* represents growth rate of the area (percentage), and *t* is the planning horizon (years).

Case Study

In this study, the drainage infrastructure of Neu-Götzens, an Alpine city in the proximity of Innsbruck/Austria, with a connected area of 22 ha, is selected as the case study. The existing combined drainage network will be completely rebuilt as separate system in the next years. The initially planned new stormwater network is a dendritic one. However, we connected all the possible conduits within the area to resemble a grid-like network as the base sewer system (Figure 1) to cost efficiently improve the performance.

Results and discussion

With respect to the weight assigned, applying Equation (1) to the grid-like base system led to the identification of 40 additional pipes (formed loops) in the network as depicted in red color in Figure 1a. Afterwards, applying Equation (2) to the six original return periods introduced before, led to the new recurrence intervals as RP = {3.2, 4.8, 8.1, 16.1, 32.2, 48.4, 80.6, 161.2 and 322.44} to account for urbanization impact regarding the region's growth rate equal to 1% and planning horizon equal to 25 years. These return periods were then utilized to evaluate the hydraulic performance of all created structures in terms of flood reliability. Among 3,280 generated configurations, the best compromise candidate between flooded volumes, flooded nodes and the number of additional pipes were detected; hereinafter is called "optimal network". The characteristics of this network were consequently compared with the branched and looped (base) storm sewer network. As seen in Figure 1a, the optimal network is composed of only 18 (out of 40) additional alternative flow paths (shown in orange colour). Comparing all three networks reveals that networks with a more branched structure observed a smaller number of flooded nodes (Figure 1b). This is because once the system capacity is fully utilized in a looped system, multiple flow paths cause more nodes to flood. In terms of surface flooded volume, eliminating all extra pipes from the base system except from the 18 pipes (optimal network), not only did not aggravate the increased runoff discharge (as normally expected due to the reduced total storage capacity), but also slightly reduced the flooded volume generation under all rain events (see Figure 1b). Thus, these 18 additional pipes can be deemed as critical pipes at appropriate locations, whose presence single-handedly delivers an efficient and quick discharge of high precipitation rates out of the system.



(a) (b)

Figure 1. (a): Base (looped) stormwater pipe network of the case study including the location of (critical) additional pipes (as in optimal network). (b): Hydraulic performance of looped (grid-like), optimal and branched networks in terms of flooded volume and flooded nodes based on nine storm rain events.

According to Table 1, although the total system capacity of the looped network (with total costs of €2,287,000) is greater by the value of 53 m^3 than that in optimal one (with total costs of €2,126,000), the optimal network's performance demonstrated less surface flood production as aforementioned. This highlights the importance of the location of 18 additional pipes in the optimal network through which peak runoff is distributed more efficiently, though its capacity was less than that in looped one. Considering Figure 1b and Table 1, branched network (with total capacity and cost of 705 $m^3$and €1,912,000 respectively) where only unique pathways for discharging peak runoff exist, yielded more flooded volumes.

Table 1. Looped, branched and optimal network characterises in terms of total system capacity and total system costs.

Total capacity/costs Networks	Total system capacity [m^3]	Total system cost [€]
looped network (40 loops)	831	2,287,600
Optimal network (18 loops)	778	2,126,000
Branched network (no loops)	705	1,912,400

Conclusions and future work

Identification of sensitive locations to construct loops is of high relevance, which might either improve the flow distribution or exacerbate it. For this purpose, a novel methodology based on topological network characteristics was introduced in this study to quickly create numerous configuration candidates with different structural characteristics to infer the optimal layout and the desired-loop locations. This framework can be additionally deemed as a valuable tool for rehabilitation purposes such as pipe replacement.

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