2nd International Joint Conference on Water Distribution Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14738

INFRASTRUCTURE BENCHMARKING FOR SEMI-REAL URBAN STORMWATER NETWORKS

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Abstract

Attaining accurate information on the underground urban drainage/storm networks is a very difficult task, specifically in (developing) countries undergoing urban expansion. The problem of limited data availability gets even worse when considering that most case studies cannot made public due to security reasons. This, therefore, shed light on the lack of possessing enough case studies with different topological characteristics/attributes for the urban drainage research community to regularly explore and exploit their strategies/methodologies in a unified and integrated manner, allowing scholars to analyse and even compare their implications.

To cover this research gap, we developed a ready-to-use open-access database of a multitude of (semi) real urban stormwater case studies with different characteristics. Specifically, optimized centralized and decentralized stormwater networks are considered for creating the benchmarks while redundant flow pathways are introduced into these structures (by leveraging complex network analysis) to create more diverse characteristics. This allows that if for a real case study area, no further information is available (e.g., developing countries), with the proposed approach, a feasible model for principal evaluations can be created with very low efforts. We expect more scholars join this momentum in the future by adding more case studies with various attributes to form a comprehensive and rich database not only in terms of hydrodynamic models and case studies but also digital sensors and observation data (e.g., flow meter, rain gauge data, etc.).

Keywords
Urban drainage networks, benchmarks, optimization, redundancy, functional resilience.

1 INTRODUCTION

Urban drainage networks (UDNs), specifically urban stormwater networks (USNs), are essential assets within the cities, responsible for protecting citizens from potential urban flooding and ensuring preservation of the environment. Due to the complexities and detailed description of input information entailed in their modelling and simulation, various spectrums of approaches, methods, and technologies have been continuously deployed and tested by scientists to improve different aspects of UDNs performance. These include design [1], [2], resilience [3], [4], quality issues [5], rehabilitations [6], [7], etc. However, the implications from these studies are oftentimes case-specific, and therefore not allowing to draw generic conclusions. This is because these results were often derived from analysis of a single case study, which may not be a good representative of the underlying mechanism and the process. The reason is partly due to the fact that getting accurate and detailed structural/hydraulic information and model on the underground infrastructures. Specifically UDN/USN is a tedious task [8]–[10]. In addition, this data, including detailed layout or sewer/inlet locations, sewer dimensions, materials, sewer slopes, are often non-existent (due to aging, errors and missing information) or not publicly available by water utility companies due to security and publicity reasons. Thus, such a lack of universal and commonly accepted benchmark database hinders hydrological and hydraulic scholars for exploring, exploiting and comparing their developed methodologies/approaches to reach a unified consensus model.

Availability of open data and uniform benchmarks can be found more within the field of water distribution networks (WDNs) [11]–[16]. In contrast, such attempts have been rather limited in the domain of UDNs. For example, M Möderl et al., (2009) developed a MATLAB tool "Case Study Generator" for the generation of virtual combined sewer systems (CSSs) wherein the layout of the sewer systems is based on an adapted Galton-Watson branching process [17]. R Sitzenfrei et al., (2010) developed an innovative software called VIBe (i.e., Virtual infrastructure Benchmarking) for algorithmic generation of virtual case studies (VCSs) for UDNs (combined sewer systems) and WDNs [14]. Urich et al., (2010) developed an agent-based approach to generate virtual CSSs as an extra module integrated into the VIBe software [13], [18]. However, despite being pioneers in the domain of virtual case study generation, the aforementioned frameworks did not entirely represent and capture the real-world characteristics of these structures. For example, a very simple layout procedure was utilized in these studies without considering road networks. This is because road networks are often viewed as a proxy for sewer layout representation thanks to their strong correlation with drainage layouts [19]. Further, very simplified hydraulic dimensioning was used in these studies, such as Rational or time-area method [20]. Blumensaat, Wolfram, & Krebs, (2012); Duque, Bach, Scholten, Fappiano, & Maurer, (2022), further integrated street network information in addition to other freely available data for the creation of more realistic sewer systems [21], [22]. Also, Nedergaard Pedersen et al., (2021) presented a comprehensive and unique real-world data-access data set, with the provision of existing meters, sensors and gauges in the real-world network [23]. Although these studies provided alternative databases for the drainage community while capturing a clearer picture of the real-world infrastructures, most of them are either computationally and/or mathematically expensive to reproduce or not open access for community to easily and quickly harness their potentials. Moreover, none of the mentioned efforts provided a great number of (optimal) ready-to-use semi-real-world USNs with different topological characteristics. As a result, in this study, we publish an open-access database of a multitude of optimized (semi) real USNs with different properties (e.g., diverse number of redundant flow paths). These networks employ complex network analysis for the design and adding redundant flow paths. Then, one specific application/modelling aim of this database is investigated in terms of functional resilience performance (i.e., evaluating flood characteristics of the networks under low to heavy storm events). However, this database can be used for any other applications such as structural resilience (i.e., sewer/inlet blockage), green-blue infrastructure analysis, etc.

2 METHODS

2.1 Complex network analysis of UDNs

UDNs can be analysed using a mathematical branch called graph theory G wherein the sewers, weirs and pumps are represented by the edges (E) of the graph and inlets/manholes and outlets are represented by the vertices (V) of the graph. Graphs are often represented by adjacency matrix A, in which its entry $a_{ij} = 1$ if there exists an edge between the source and target nodes of the graph (i, j), and $a_{ij} = 0$ otherwise. Thus, matrix A is V by V dimensions. To reproduce the properties of USNs; first, the graph needs to be directed since UDNs are primarily gravity-driven by specific and defined directions (e.g., based on their slope or flow directions); and second, USNs-tailored graph weights must be defined and allocated to vertices and/or edges of the graph depending on the purpose of the modelling (e.g., sewer lengths, diameters, velocity, etc.). These weights are given to the graph to mimic the structural and/or functional characteristics of the USNs, facilitating the relevant analysis. In this work, we use Eigenvector centrality measure [24], [25], to identify the sensitive locations/inlet nodes for initiating the redundancy construction.

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This measure is a generalization of node degree centrality, (i.e., the number of edges connected to a node). Eigenvector centrality (shown in Eq. 1) indicates that a node can gain high eigenvector centrality not by having a high degree of centrality but also by being connected to nodes which themselves have high centrality. This measure is used to rank and score the nodes for constructing redundant paths for creating our benchmark database. Sewer diameters are used as edge weights/importance to detect the nodes interacting directly and indirectly with large pipelines of the UDNs.

$$\lambda c_i^E = \sum_{j=1}^{\#V} a_{ij}\, c_j^E \quad (1)$$

where, $i = 1, 2, \dots, V$, are the nodes, λ is a constant eigenvalue, c_i^E is the eigenvector centrality of node i, c_j^E is the eigenvector centrality of other neighbouring nodes relative to node i, and a_{ij} are the entries of adjacency matrix A.

2.2 Optimization of USNs

Starting with the base graph (e.g., street network), sewer layout generation is initiated to infer e.g., flow directions. Leveraging complex network analysis, a deterministic multi-objective optimization (brute force method), and a set of layout objective functions (based on ground slope, sewer length and cumulative runoff area), a great number of layouts were generated, pre-screened and discarded. Then, due to contradicting layout objective functions (e.g., maximizing negative lopes and minimizing runoff distribution), the Pareto front of the best performing layouts were obtained. These solutions lying on the Pareto front were then forwarded to the SWMM-based hydraulic optimization to finally infer the optimal (decentralized) layout as well as the best-centralized layout. To quantify the degree of topological centralization, the generic measure introduced in [1] is used shown in Eq. 2:

$$DC = 100 \times \left(1 - \frac{log_{10}^{ON_s}}{log_{100}^{IN}}\right) \ (\%) \quad (2)$$

This measure has a logarithmic relationship between the number of (selected) outlet nodes (ON_s, at most IN -1) and the total number of inlet nodes (IN). This measure indicates that e.g., if one outlet node is selected among the outlet candidates during the layout optimization process, the DC is equal to 100% or a fully centralized system.

Hydraulic design optimization is a process where after finding the optimal spatial layouts, the dimensions of sewers, slopes and whether a pump station is needed at a node, are addressed using an adaptive search approach. Meanwhile, a set of constraints are satisfied simultaneously such as minimum and maximum cover depths, minimum and maximum sewer slopes, minimum and maximum velocity and telescopic pattern for the sewers. In this work, a 2-year block rain event with a duration of 15 minutes is used in combination with the dynamic wave flow routine in SWMM5 [26] for the aforementioned processes in agreement with technical guidelines [27]. A full description regarding the layout creation procedure and hydraulic design optimization, can be found in [1].

2.3 Redundancy-promoting scenarios

In order to generate several case studies with different topological attributes, we applied herein a resilience-boosting measure called redundancy [28]. Redundancy can be enriched by adding extra storage tanks, providing extra capacity at certain locations, or introducing redundant flow pathways. It should be noted that redundancy, redundant flow paths, and loops are used interchangeably throughout this manuscript. In this work, the latter attribute (i.e., redundant flow

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paths) is introduced to the optimized centralized and decentralized layouts, which originally do not have any redundant paths (loops). The redundant paths are added based on three strategies. (1) introducing redundant paths from upstream sections towards downstream sections, (2) introducing redundant paths from downstream sections towards upstream sections, and (3) introducing redundant paths from certain locations determined by Eigenvector centrality (Eq. 1). These redundant pathways are introduced cumulatively to the designed centralized and decentralized solutions based on the mentioned three strategies until achieving the maximum number of loops. Based on the design characteristics and the candidate nodes to construct redundant paths, two situations may occur (Fig. 1). Note that if constructing redundant flow paths from a node imposes the decentralized solution connected, we exclude that node from the redundancy candidacies. For example, nodes T, S and R, are those whose connections turn the decentralization notion of the network into a centralized one. Therefore, only node Q is considered in the example below to construct a redundant path (Fig. 1).

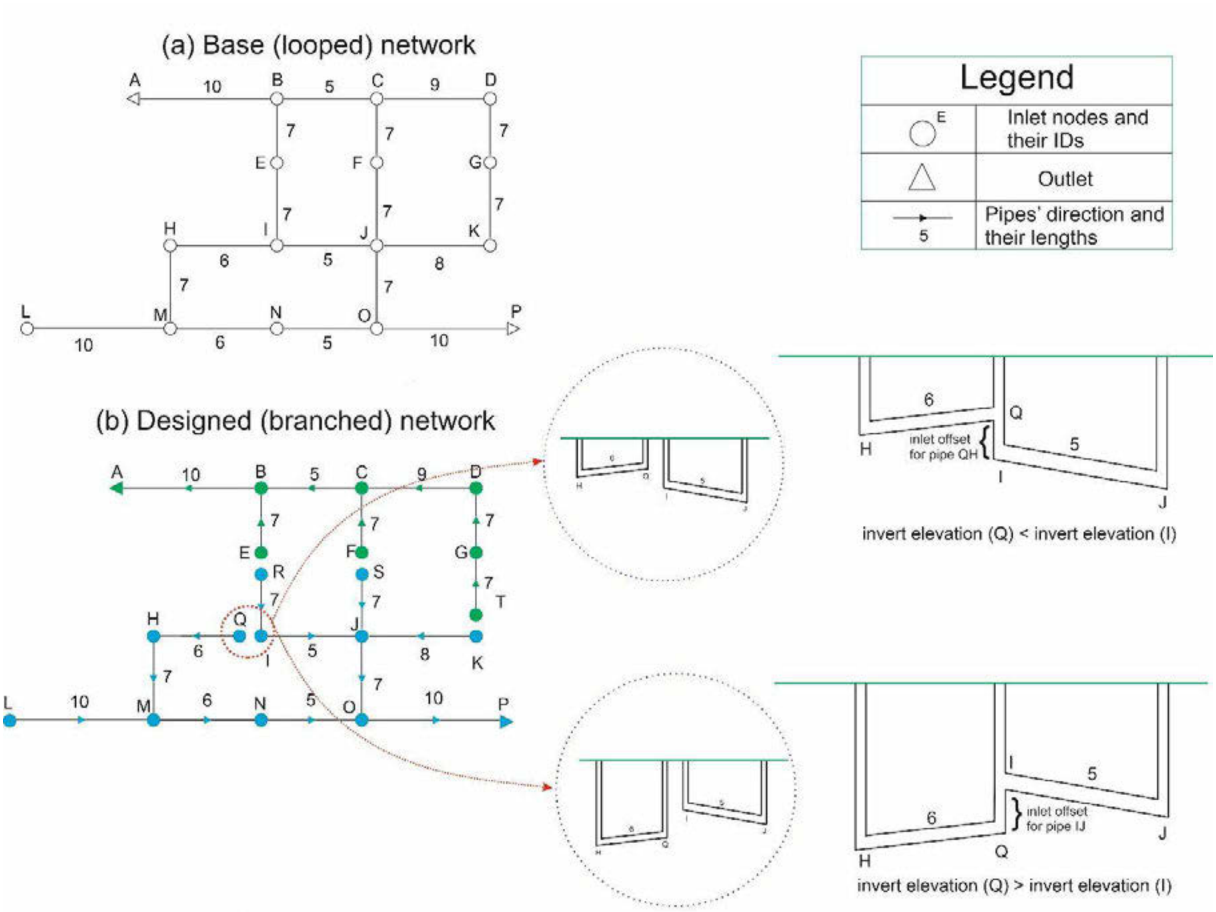

Figure 1. Pedagogical example of redundancy-promoting strategies [29] *(under review).*

2.4 Resilience evaluation

As mentioned earlier, a 2-year block rain event is used to design all USN solutions, achieving a limited/specific drainage capacity. However, due to the ongoing climate-change precipitation events, infiltration rate and drainage capacity of USNs are frequently exceeded, leading to flooding events out of the manholes. Thus, functional resilience of the USNs is evaluated in this study under medium (10-year) and extreme rainfall events (50-year) according to Eq. 2.

$$HPI = 100 \times (1 - \frac{V_{flooding}}{V_{runoff}}) \quad (\%) \qquad (2)$$

Where, HPI represents the hydraulic performance indicator, $V_{flooding}$ is the total ponded flood volume [m^3], and V_{runoff} is the total runoff volume [m^3].

2.5 Case study

The investigated case study area is a part of Innsbruck (a steep region), an alpine city in Austria, as shown in Fig. 2 with around 15-meter difference in ground elevations. The free available data is an open street map from *https://www.geofabrik.de*, 30-m resolution digital elevation model (DEM) from *https://srtm.csi.cgiar.org*, and 20-m impervious layer map from *https://land.copernicus.eu* integrated into a base graph, upon which the (de)centralized design solutions are created and designed. It is worth mentioning that the subcatchments were delineated according to Voronoi diagrams or Thiessen polygons [30], [31]. This network with 11 potential outlet locations in the proximity of the river Inn is depicted in Fig. 2 with their characteristics as presented in Table 1. This case study is then designed based on two structures (centralized and decentralized) while redundant paths are added to them cumulatively. During this process (except for two branched centralized and decentralized networks), 200 networks are created for centralized system based on each redundancy-constructing strategy, and 139 networks for decentralized structure. In other words, 600 (200 × 3 strategies) networks are created for centralized solution with different number of loops, and 417 (139 × 3 strategies) networks are created for decentralized solution with different number of loops, leading to an overall 1019 USNs. More details regarding this case study can be found in [1].

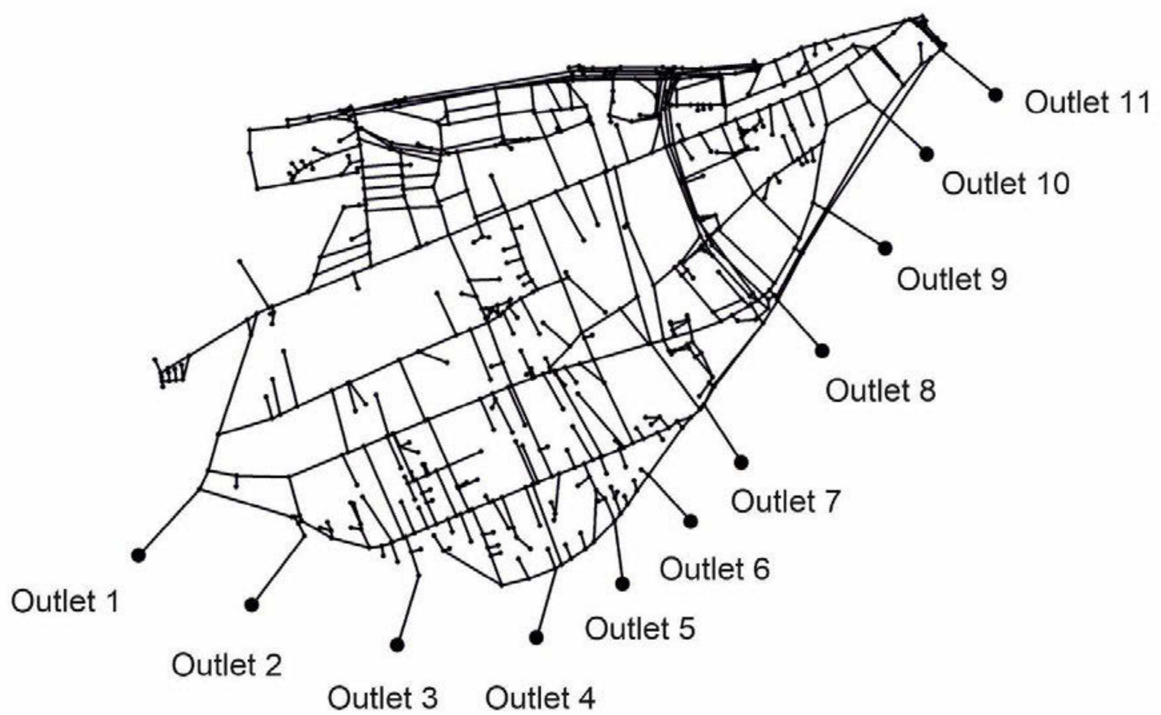

Figure 2. Case study (fully looped base graph/street network): a steep area within the city of Innsbruck [1].

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Table 1. Characteristics of the case study [1].

	Total number of nodes	Total number of pipes	Total number of Subcatchment	Total lengths (m)	Average pipe lengths (m)	Total area (ha)	Total runoff area (ha)	Total number of outlet candidates	Elevation (m)
Case study	700	913	700	50,712	55.54	188	100	11	583 - 568

3 RESULT & DISCUSSION

Once the optimal centralized and decentralized layouts were chosen and hydraulically designed (shown in Fig. 3), they were benchmarked as the backbones of the database, to which redundant paths are introduced, thus, forming our whole database. As can be seen, the capital savings resulting from decentralization far outweighed the centralized design with construction cost (CC) as two times cheaper, emphasizing the significance of the decentralized solution. The DC measure of the optimal (decentralized) solution (Fig. 3b) is equal to 68%.

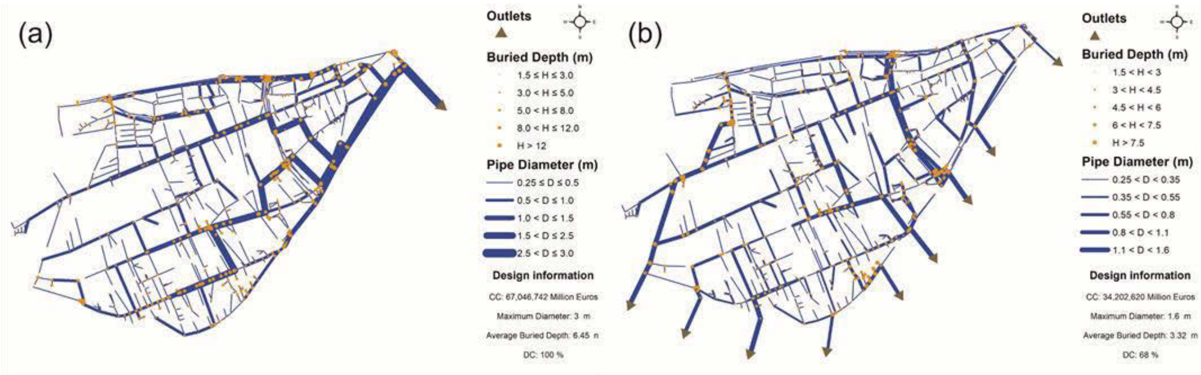

Figure 3. Purely centralized design on the left and optimal (decentralized) design on the right for city of Innsbruck (steep area) [1].

Thereafter, the redundant flow paths are added to the two structures (based on three strategies explained above), forming our benchmark database. As mentioned before, the functional resilience of this dataset is analysed in this paper, however, any other applications can be performed, such as structural resilience (i.e., sewer/inlet blockage), green-blue infrastructure analysis, etc.

Fig. 4(a) and (b) show the resilience (via HPI) performance under low-medium rain (i.e., 10-year event with total rain amount equal to 53.94 mm, having 15 min durations) where (a) denotes its distribution with extra paths constructed from upstream and downstream (with the implication from the branched network), and (b) represents the HPI values against the percentage of loops with the implication from (eigenvector) centrality-based strategy. Regarding the resilience response of networks, the influence of flow redistribution achieved via redundancy is lessened due to the steepness of the catchment, thus, minor flood volume is expected. As seen in Fig. 4(a), the branched decentralized layout slightly outperformed its centralized counterpart.

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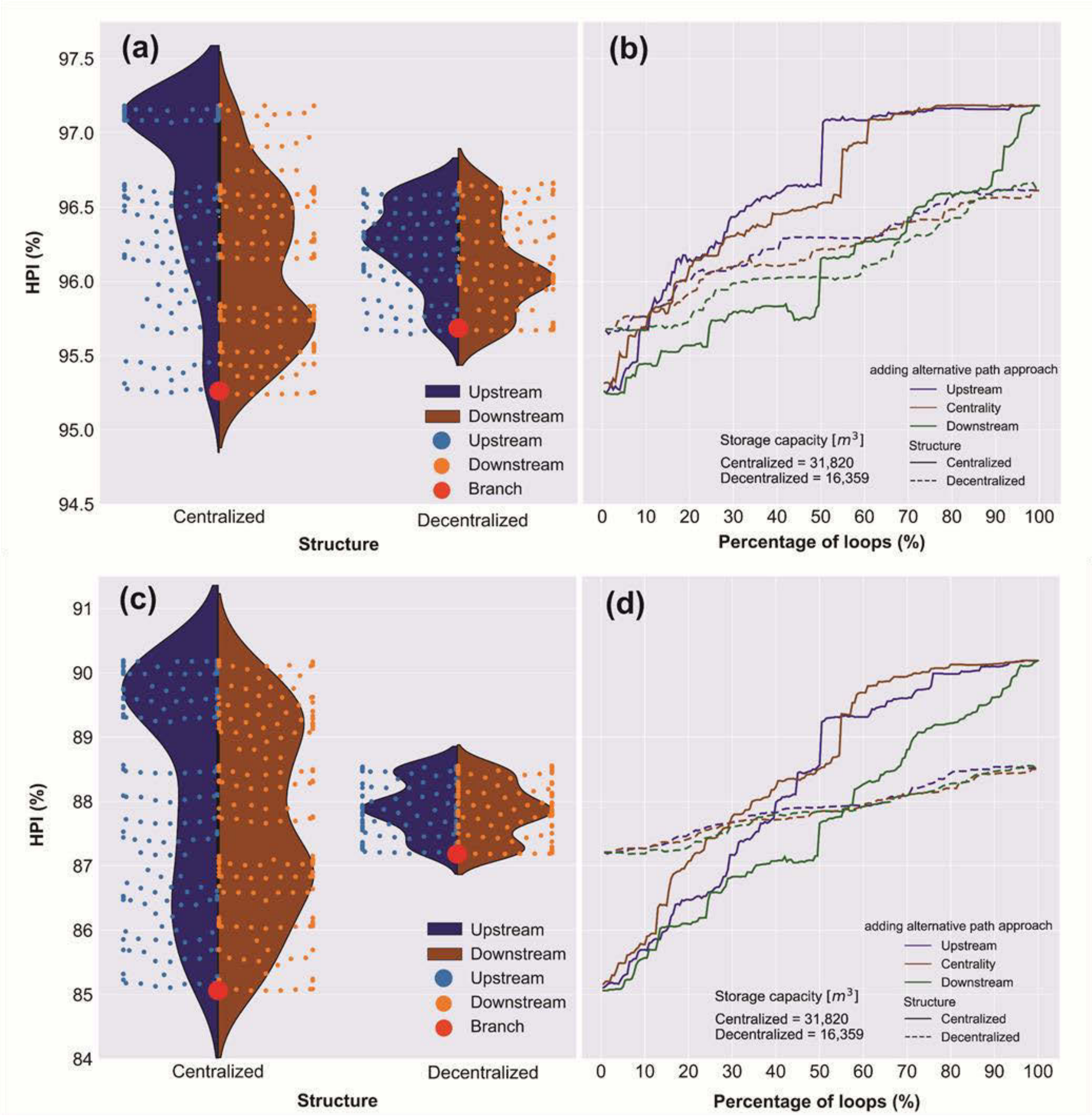

Figure 4. Resilience performance (HPI measure) of centralized and decentralized networks in the city of Innsbruck (case study) while redundancy (alternative water flow paths) is added using upstream, downstream and centrality approaches. Fig. 4(a) and (b) are the performances under the 10-year rain event, and Fig. 4(c) and (d) are the performances under the 50-year rain event.

Additionally, Fig. 4(b) shows that placing cumulative alternative water paths from upstream yielded better resilience with more concentration of HPI values around 97% for centralized and 96% for decentralized solutions. Considering Fig. 4(b), adding alternative pathways into the centralized layouts elevated the resilience (ranging by 2%) quicker than decentralized ones (ranging only by 1%), primarily thanks to its (centralized) bulky storage capacity as well as more effective flow direction achieved by redundancy. Furthermore, there existed a close competition between the resilience response achieved via upstream and centrality whereas, downstream loops underperformed the other two strategies.

However, concerning extreme precipitation (under 50-year event with a total rain amount of 72.75 mm with 15 min duration), shown in Fig. 4(c) and (d), it can be inferred that the range of variations for the decentralized network still remains very limited by only 1% resilience

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improvement once all extra paths were cumulatively constructed. This quantity, however, changed by 5% for the centralized layout. This fact demonstrates the relative inefficiency of introducing redundancy into decentralized layouts in steep terrains because the catchment steepness combined with decentralization (at the design stage) could sufficiently attenuate the extreme flood discharges out of the system.

4 CONCLUSIONS

When different applications and modelling purposes of UDNs are evaluated, the generalization of results is often feasible if methodologies are applied to a great number of case studies. However, attaining accurate and detailed structural and hydraulic information/model on the underground UDNs is not a trivial task. Moreover, water utility companies are often not interested in sharing their data due to security and publicity reasons. Thus, to take a small step to bridge this research gap, this study aims to develop a case study benchmarks for the urban drainage community by providing an optimized centralized and decentralized semi-real-world case study with various topological variations (i.e., existence of different number of redundant flow pathways). This database can be reached through (https://github.com/iut-ibk/Benchmark-CaseStudies-Innsbruck.git) for the steep region discussed herein. Then, this dataset was used as the benchmark case study to evaluate the networks' functional resilience under low and high precipitation events. However, any other applications can be also performed such as structural resilience (i.e., sewer/inlet blockage), green-blue infrastructure analysis, etc. The results indicated the efficacy of decentralized scenarios for mitigating volumetric flow discharges (especially under heavy storm events) compared to centralized scenarios. The results also showed the suitability of Eigenvector centrality to identify the sensitive locations for the introduction of redundant flow pathways.

Note that, the same framework conducted in this study, is already applied to an entirely flat region in city of Ahvaz/Iran, whose publication is currently under review [29]. The database used in [29] can be also found through (https://github.com/iut-ibk/Benchmark-CaseStudies-Ahvaz.git).

5 ACKNOWLEDGEMENTS

This study was funded by the Austrian Science Fund (FWF): P 31104-N29.

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