Meshness of sewer networks and its implications for flooding occurrence

Julian David Reyes-Silva, Björn Helm and Peter Krebs

ABSTRACT

Understanding the factors that affect the occurrence of failures in urban drainage networks (UDNs) is a key concept for developing strategies to improve the reliability of such systems. Although a lot of research has been done in this field, the relationship between UDN structure (i.e. layout) and its functional failures is still unclear. In this context, the present study focuses first on determining which are the most common sewer layout topologies, based on a data set of 118 UDNs, and then on analyzing the relationship between these and the occurrence of node flooding using eight subnetworks of the sewer system of Dresden, Germany, as a study case. A method to 'quantify' the topology of a UDN in terms of similarity to a branched or meshed system, referred to as Meshness, is introduced. Results indicate, on the one hand, that most networks have branched or predominantly branched topologies. On the other hand, node flooding events in networks with higher Meshness values are less likely to occur, and have shorter durations and smaller volumes than in predominantly branched systems. Predominantly meshed systems are identified then as more reliable in terms of flooded nodes and flooding volumes.

Key words | function, reliability, structure, topology, urban drainage

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INTRODUCTION

Over recent years, studies regarding the reliability of urban critical infrastructure networks, i.e. their capability to operate at a satisfactory level most of the time while minimizing failure frequencies, have become more relevant due to the increasing threats and uncertainties posed by global phenomena such as climate change, rapid urbanization processes and population growth. Both water supply and urban drainage networks (UDNs) are examples of such critical infrastructure networks. Studies on reliability of drinking water supply systems have focused, on the one hand, on the identification of critical structural components (Martinez 2010; Yazdani *et al.* 2011), and on the other hand, on the analysis of system performance under diverse adverse scenarios. In order to express reliability in an analytical way, network resilience indexes are calculated and used as a surrogate measure of reliability. Studies have analyzed several hazard categories, such as diverse operational conditions (Jayaram & Srinivasan 2008; Reca *et al.* 2008; Creaco *et al.* 2014), over-demand (Baños *et al.* 2011) and hydraulic or mechanical failures (Prasad & Park 2004). Regarding UDNs, studies have analyzed reliability in terms of pipe-related failures such as blockages (Rodríguez *et al.* 2012; Haghighi & Bakhshipour 2016) and deterioration (Mahmoodian & Alani 2013; Tran 2016), and with respect to node flooding (Thorndahl & Willems 2008; Lee & Kim 2019; Wang *et al.* 2019).

Intervention strategies for UDNs aim to achieve a systems status where the frequency of failures, e.g. node flooding, is minimized while maintaining an adequate level of service and being able to efficiently recover from hazards (i.e. a system that is reliable and resilient), through sustainable solutions. Butler *et al.* (2016) introduced a framework to support the development of intervention strategies taking into account different threats and water system state categories. Casal-Campos *et al.* (2018) analyzed the resilience, reliability and sustainability of gray, green and hybrid intervention strategies in UDNs. Their results suggest that

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combined solutions with green retrofits and gray rehabilitations (i.e. hybrid strategies) are more sustainable. In this context, structural and functional failures in UDNs, e.g. pipe blockage or node flooding, and their potential solutions using gray, green or hybrid intervention strategies, are well understood and described.

In contrast, previous studies have neglected implications of UDN layout (i.e. physical arrangement) on performance and hence on reliability. Traditionally, drainage systems are designed to collect and transport wastewater in a cost-effective way. Optimal layouts include the least number of pipes or smallest total pipe length, thus resembling tree-like structures. Such design approaches disregard the effects that additional pipes might have on system behavior. Examples of layout analyses in urban water networks mostly focus on water supply networks. Yazdani & Jeffrey (2012) and Martinez (2010), for example, suggested that the reliability of a water distribution network improves with the presence of extra pipes, i.e. networks with a meshed-like layout, since it adds redundancy to the system. However, similar studies for UDNs are rare. Zhang *et al.* (2017) suggested that UDNs with a fully meshed layout are less vulnerable to structural failures such as pipe blockage and tend to be more stable than branched systems (i.e. with a tree-like layout). Lee *et al.* (2018) analyzed the influences of different stormwater network structures on the relationship between peak rainfall and runoff. Results of this study suggest that networks with higher drainage density, i.e. with a more meshed layout, are inducing lower runoff peaks than branched systems. Although these are interesting findings, the application of such analyses to existing sewer systems might be challenging. Evolution and growth processes of cities often result in a heterogeneous layout of UDNs, mixing both grid-like and branched configurations. In this context, two main questions arise: (1) what is the most common topology of UDNs and how frequently do branched and meshed sewer layouts occur in real networks? And (2) which of these topologies is more reliable in terms of functional failures?

The present work focuses on answering these two questions. Such analyses require a metric to determine how close a UDN layout resembles a branched system or a grid-like pattern. Buhl *et al.* (2006) introduced the 'meshedness coefficient', a graph-theory-based parameter to determine the structure of street networks. Although this coefficient has been used to analyze the structure of water supply networks (Yazdani *et al.* 2011; Yazdani & Jeffrey 2012), its application for UDNs seems inadequate. To overcome the limitations of such an approach, a new method to calculate a coefficient, here referred to as 'Meshness', for the analysis of UDN layouts is introduced. The approach is based on graph-theory concepts, i.e. the study of structures formed by pairwise relations between objects (Elsner *et al.* 2009). Such approaches rely only on the connectivity data of the network (i.e. identification of starting and ending nodes of each pipe section), thus reducing the requirement for comprehensive data. Typical UDN topologies are analyzed with a data set of 118 networks and subnetworks, obtained from sewer system information of 32 cities in Europe, America and Asia. Furthermore, the relationship between UDN layout with the occurrence of functional failures, due to node flooding events, is analyzed for eight subnetworks of the drainage system of Dresden, Germany. For these networks hydrologic–hydrodynamic models implemented in the EPA Stormwater Management Model (SWMM, Rossman 2015) are available (Kaeseberg *et al.* 2018).

MATERIALS AND METHODS

Meshness calculation method

As mentioned above, the metric 'meshedness coefficient' to analyze the structure of spatial networks such as streets and water supply systems was introduced by Buhl *et al.* (2006). Nevertheless, it is not considered suitable for UDNs. On the one hand, this parameter corresponds to the ratio between the total and maximum number of independent triangular loops in a planar graph. A value equal to zero represents tree structures while a value of one represents a complete planar graph. Triangular loops, however, rarely occur in UDNs. On the other hand, the presence of additional pipes, which lead to meshed layouts, occurs typically at the inner sections of the network, since multiple connections at the source (headflow) or outlet nodes are rare. By including these nodes in the structural analysis, the maximum number of potentially independent loops is overestimated. Unrealistic loops resulting from potential connections among the source and outlet nodes lead to low values of the current meshedness coefficient and possibly underrate important structural characteristics in the inner section of the network.

To overcome these limitations, a new metric for analyzing UDNs' structures is developed. Such a parameter, referred to as Meshness here, is based on the degree of connectivity of the inner nodes, i.e. the number of pipes connected to junctions, except source or outlet nodes. To perform the required analysis, UDNs are interpreted as directed graphs (G = (E, V)), where the nodes (V), usually representing manholes, are the junctions between pipe sections, which correspond to edges (E) with a constant direction. The proposed method is illustrated in Figure 1 and Table 1. The hypothetical network on the left with black edges corresponds to the original UDN layout whose Meshness needs to be determined. As a first step, nodes with a total degree *K* (i.e. total amount of connected pipes) higher than 1 ($K > 1$) are selected as the inner nodes (represented as black dots in Figure 1). This is done under the assumption that source or outlet junctions can only have one pipe connection and therefore do not contribute to the Meshness of the network. Subsequently, the degree of each inner node is calculated and summed up. As a result, in the current example nine inner nodes and a total of 32 connections are identified, corresponding to an average of 3.5 pipes connected per node. This value, here referred to as the Average Total Degree (ATD), is the basis for calculating the Meshness of the network. In meshed systems, nodes have a larger number of connected pipes, and hence higher ATD values.

It is assumed that increments of Meshness due to increased connectivity (expressed as ATD) follow a linear trend. To derive such an expression, ATDs corresponding to the boundary values of 0% and 100% Meshness need to be determined first. On the one hand, it is assumed that in a fully meshed system, i.e. Meshness = 100%, all inner nodes can have a maximum of four connected pipes (due to topographic and construction restrictions), thus leading to an ATD = 4. Exceptional cases with five or more connections at one point, that may result from triangular or delta pattern road networks, are ignored. On the other hand, it is hypothesized that a 0% Meshness value represents a network configuration with the least number of pipes without causing any disconnection. Such a layout and its elements correspond to the Minimum Spanning Tree (MST) configuration of the analyzed network, since it is a subset of the original graph where all nodes are connected without any cycles and with the minimum sum of edge weights. MST configurations are determined here using Kruskal's algorithm (Kruskal 1956) with the lengths of each pipe section as edge weights. Length serves as a surrogate variable for travel times in the system, where shorter lengths imply shorter times. The MST layout obtained can then be interpreted as the network configuration with the least number of pipes without causing any disconnection that transports wastewater in the fastest way (minimum sum of edge lengths and therefore minimum sum of times). Since MST layouts are case-specific, ATD values for this type of configuration are not constant and therefore need to be determined for each individual UDN. This is done first by calculating the new number of total connections of the inner nodes (identified in the beginning) in the MST configuration, and then dividing by the original number of inner nodes. The proposed method for calculating Meshness is implemented in MATLAB™. Each

Table 1 | Total number of connections, inner nodes and ATDs for the Meshness calculation of a hypothetic UDN

	Total connections [–]	Inner nodes [–]	ATD [connections/ node]	Meshness [%]
Original	32	9	3.556	50
MST	28	9	3.111	0
Fully meshed	36	9	4	100

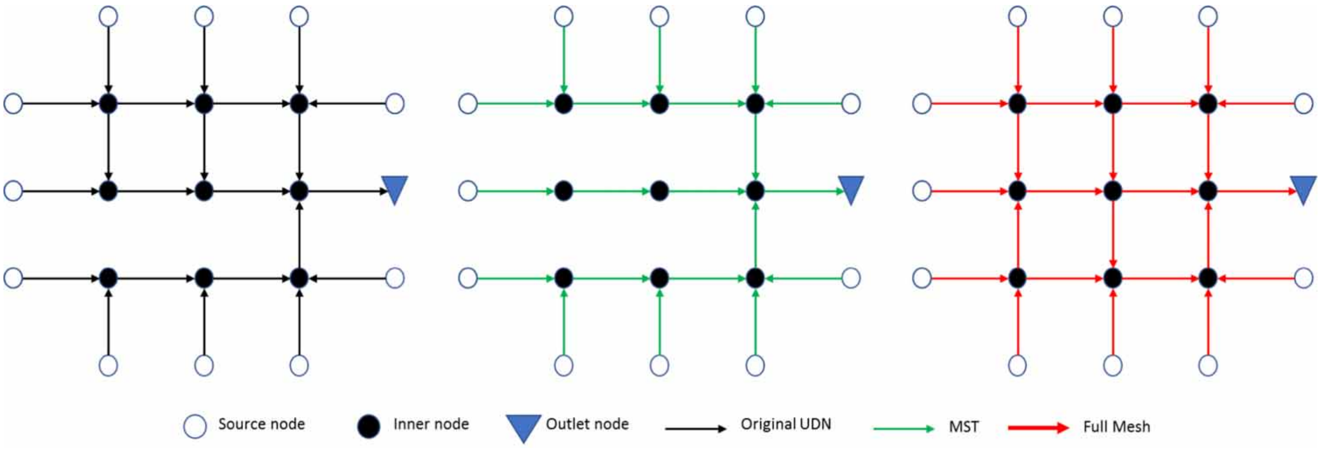

Figure 1 | Original (left), MST (middle) and fully meshed (right) layouts for the Meshness calculation of a hypothetic UDN.

network is considered as a directed graph element and built-in functions for network analysis are used for calculating total degrees (i.e. number of connected pipes) and determining the pipes corresponding to the MST configurations.

Figure 1 exemplifies the procedure for the hypothetical network. As mentioned before, the left panel shows the original network with nine inner nodes in black and 32 connections, also in black, resulting in an ATD of 3.5. The MST configuration, represented as the network with green edges in the middle panel, consists of only 28 connections and an ATD of 3.1. Finally, the fully meshed network in red on the right side has 36 links and therefore an ATD of 4. Once the ATD values corresponding to the limiting cases (0% and 100% Meshness) are determined, the Meshness of the original layout is then calculated by linear interpolation. For the hypothetical example, Meshness is 50% and Table 1 includes all numbers. This value indicates that 50% of the network layout corresponds to meshed structures, while the rest is branched.

Case studies

In an urban area, several independent drainage network structures can coexist due to different construction customs and infrastructure evolution throughout time. On the one hand, multiple drainage systems in cities with a traditional combined sewer network scheme are associated with the presence of multiple outlets, e.g. wastewater treatment plants and combined sewer overflow structures. On the other hand, urban areas with a separate sewer scheme are comprised of parallel and independent sewer systems for the collection of sanitary sewage and stormwater. Furthermore, hybrid schemes, i.e. presence of both combined and separate sewer systems in one town, occur frequently, thus increasing the presence of independent drainage networks.

Availability of structural data of UDNs is, however, often limited due to security reasons or privatization of the information. In this context, a data set of sewer systems from 32 cities (20 from Europe, ten from North America, one from South America and one from Asia), obtained from different public and private sources, is used for the desired analysis. The minimum requirement for the selection and usage of these data is the availability of complete connectivity information, i.e. clear identification of starting and ending nodes for all pipes, and lengths of each section. Determination of the independent subnetworks for each of the 32 sewer systems is done using the *Cytoscape* software (Shannon *et al.* 2003). The available automatic layout algorithms of the software allow a quick visual identification and selection of subnetworks in a given data set. Furthermore, built-in tools of *Cytoscape* (Remove Duplicated Edges and Remove Self-Loops) are used to check and correct the network data. Only networks with a minimum number of 150 nodes are considered. As a result, 118 independent UDNs are identified. For more information regarding the selected networks see Supplementary Data 1.

Functional failures of UDNs include overflow from manholes causing flooding volumes and durations at the surface. Often, measured data on these events are missing. Hence, only hydraulic simulations of urban areas and UDNs can provide the location of the flooded nodes, and also the magnitude and duration of such events. In this context and based on the available information, eight subnetworks from the original 118 data sets are selected for the functional failure analysis (see Figure 2). These networks are selected from the Dresden sewer system, of which hydrodynamic models implemented in EPA SWMM (Rossman 2015) are available (Kaeseberg *et al.* 2018). Information regarding the physical characteristics of these networks is provided in Table 2.

Functional failures analysis

As stated previously, hydrologic–hydrodynamic simulations are used to determine the occurrence, magnitude and duration of node flooding events for the eight study cases. Three rainfall scenarios are simulated in EPA SWMM. They correspond to 'Euler Type II' design storms (DWA-A118 2006), with reference precipitation intensities of the city of Dresden, Germany, according to the coordinated storm event intensities (Junghänel *et al.* 2017), durations of one hour and return periods of 5, 10 and 20 years, respectively. Design events are selected instead of real precipitation data in order to preserve the occurrence frequency of flooding events and, hence, systematically analyze the behavior of the networks during such conditions. In order to reduce the influence of boundary conditions on the occurrence of flood events, original catchment properties are modified. As a result, the total drainage area of all networks is equalized to 4.85 km^2 (average value of the original catchments). This is done in SWMM by equally scaling the connected areas within the subcatchments in each network. Only impervious areas are considered and similar roughness and depression storage values are assigned for all cases. Furthermore, storage tanks are converted into flow-through nodes and combined sewer overflows (CSOs) are deleted by removing the weirs and outfall elements that represent them in SWMM. This is done in order to reduce the

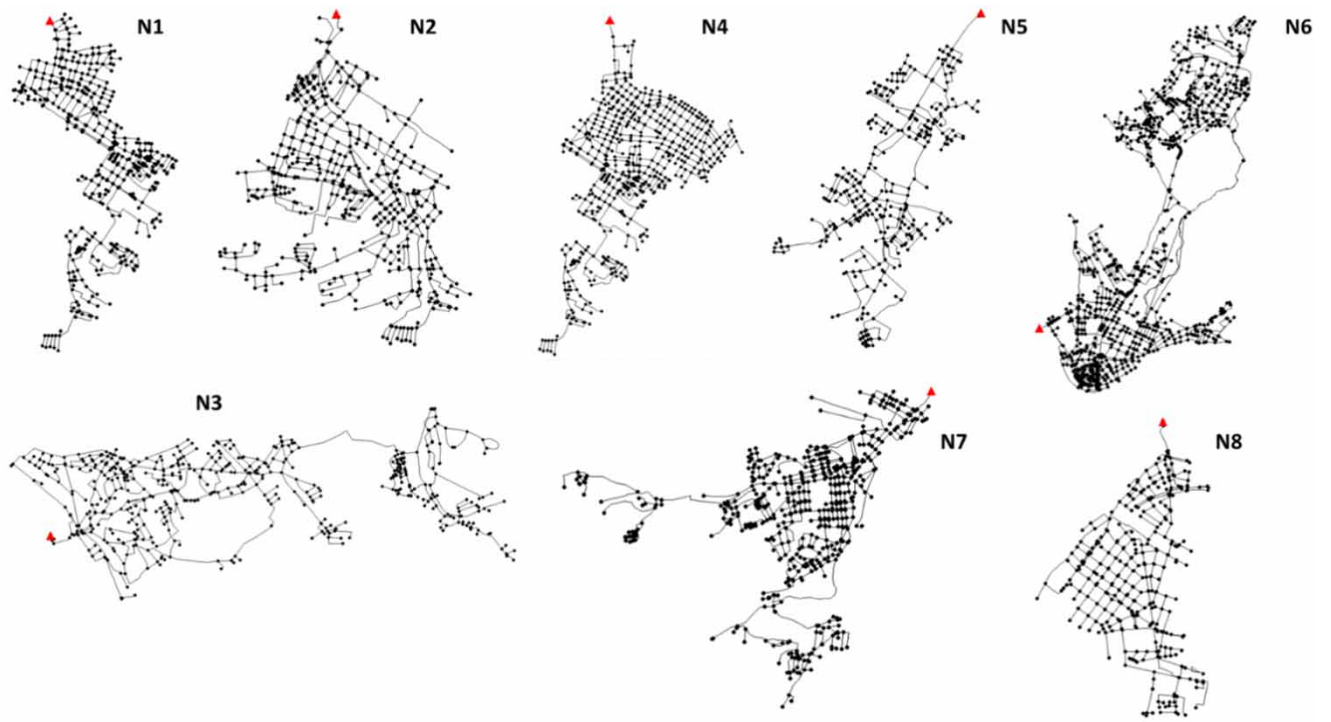

Figure 2 | Layout for the eight subnetworks of Dresden's sewer system (N1–N8). Red triangles are the outlets. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wst.2020.070.

influence of storage and outflow structures on the occurrence of node flooding.

Functional failures of UDNs in this study are comprised of: (i) the percentage of total nodes flooded for each rain event (i.e. the ratio of the number of flooded nodes and total amount of nodes in each network); (ii) the cumulative distributions of flooding volumes and (iii) durations for each network and each rain event. The Meshness value represents the network topology and is related to functional failures' measures. Reliability indexes of flood volumes and nodes serve as aggregate measures for the extent of functional failures of UDNs and their relation to the network layout. Such indexes are obtained using the following equations, proposed by Lee & Kim (2019):

$$R_{\mathrm{v}} = 1 - \frac{\sqrt{\sum_{i=1}^{n} \left(V_i/(R_i{*}A)\right)^2}}{n} \tag{1}$$

R_{v} [%] corresponds to the reliability against flood volumes, V [m^3] is the total flood volume for rain event i, R_i [m] is the rainfall height of event i, A [m^2] is the total

Table 2 | Physical characteristics for the eight subnetworks of Dresden's sewer system (N1–N8)

Network	Nodes	Edges	Area [km^2]	Sewer length [km]	Mean dry weather flow [L/s]	Mean slope [%]	Sewer storage capacity [10^4 m^3]
N1	491	551	3.54	80.13	91.58	0.86	5.26
N2	563	629	5.05	114.66	87.5	1.07	7.98
N3	575	608	3.73	76.46	67.52	2.11	2.43
N4	656	797	5.42	109.07	142.13	0.86	7.43
N5	357	384	3.64	61.92	58.88	1.08	4.52
N6	1,235	1,352	9.21	184.82	89.33	0.71	8.79
N7	621	654	5.28	102.4	143.02	2.01	6.26
N8	391	427	2.96	59.16	45.71	1.25	5.15

drainage area, and n is the number of events. In addition, reliability against flood nodes (R_n) is calculated as:

$$R_n = 1 - \frac{\sqrt{\sum_{i=1}^{n} (N_i/N_T)^2}}{n} \quad (2)$$

N_i corresponds to the number of flooded nodes during event i, and N_T is the total amount of nodes in the network. Both reliability indexes vary between 0, which represents poor reliability, and 1, a completely reliable system.

RESULTS AND DISCUSSION

Topology determination

Figure 3 depicts the Meshness distribution for the 118 analyzed UDNs. Individual values for each system are presented in Supplementary Data 1. Results indicate that most of the networks (approximately 69%, i.e. 82 systems) have branched layouts, with Meshness values lower than 5%. Furthermore, 29 systems yielded a Meshness between 5% and 25%, thus indicating that at least three-quarters of their layout correspond to branched structures. Only seven UDNs had system layouts with more than 25% of the network in meshed configurations. Based on the available data set, it was not possible to identify any example where the structure of the UDN is predominantly meshed. Regarding the eight subnetworks used for analyzing functional failures, results indicate that N3 and N7 have Meshness values below 20%, N1, N2, N5, N6 and N8 vary between 20% and 32%, and N4 reported the highest Meshness value in the whole data set with approximately 45%. The result implies that confluences with multiple up- and downstream sections are rare in most systems.

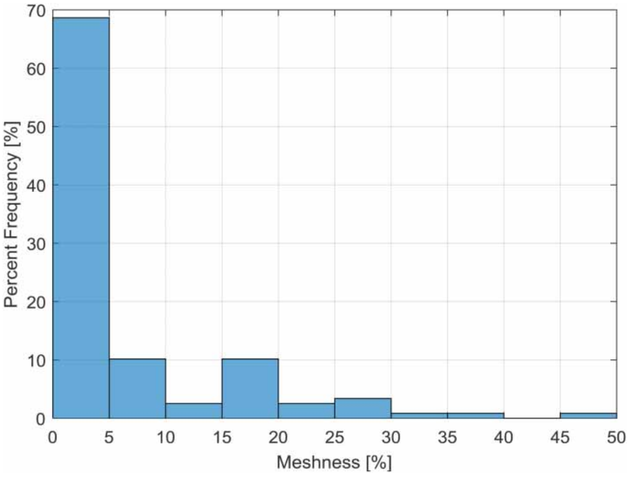

Figure 3 | Percentage frequency distribution of Meshness for the 118 analyzed UDNs.

As mentioned before, the proposed Meshness coefficient is intended to provide a metric suitable for structural analysis of UDNs. In contrast to the 'meshedness coefficient' proposed by Buhl *et al.* (2006), it focuses on the inner nodes of a UDN and thus avoids underestimating the proportion of mesh configurations in the system. The comparison of both approaches is exemplified for UDN N4. For both metrics, the system is identified as one of the more meshed networks among the study cases. Nevertheless, Buhl's meshedness yielded a value of 11%, while the proposed Meshness scored 45%. Assuming that the metrics correspond to the proportion of grid-like patterns, meshedness suggests that only a decile of the layout is meshed while by the new approach almost half the layout is accounted for as meshed. The spatial arrangement of this network (Figure 4, right panel), implies that Meshness characterizes the UDN layout more adequately. Both connectivity metrics for the 118 study cases are compared in Figure 4, left panel. Although they have a high linear correlation ($\rho > 0.9$), the 'meshedness coefficient' is consistently smaller in comparison with the proposed Meshness value of this study.

Functional failures analysis

Figure 5 presents the relationship between node flooding occurrence, in terms of percentage of total number of nodes flooded during a rain event, and the Meshness coefficient for each of the three synthetic rain events. The size of the markers is proportional to the sewer storage capacity values included in Table 2. Results imply an inverse relation between the node flooding occurrence and Meshness of each network. A potential reason for this is that increasing Meshness, i.e. increasing the presence of extra pipes, has two major effects: they (1) provide additional storage volume and (2) generate alternative flow paths. Both of these effects play a role in the reduction of node flooding frequencies.

In networks with low Meshness values, in this case lower than 25%, the presence of multiple flow pathways is not significant enough to have an impact on the occurrence of flooding events, and therefore, sewer storage volumes have a stronger influence on node flooding rates. This can be seen by comparing the results for N3 and N7. Although both networks have similar Meshness values, thus suggesting a similar number of extra pipes (proportional to each case), N7 exhibits lower percentages of flooded

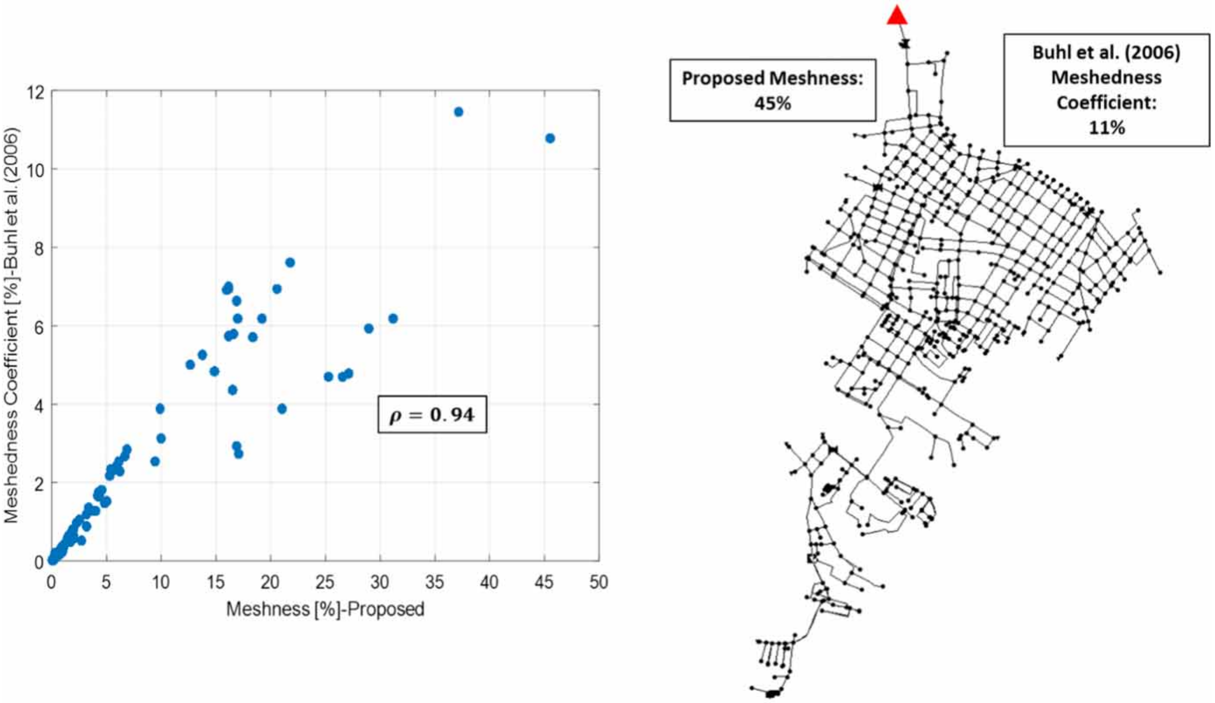

Figure 4 | Relationship between proposed Meshness and the meshedness coefficient from Buhl *et al.* (2006), including Pearson correlation coefficient ρ (left panel). Layout for subnetwork N4 of Dresden's sewer system, red triangle is the outlet (right panel). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wst.2020.070.

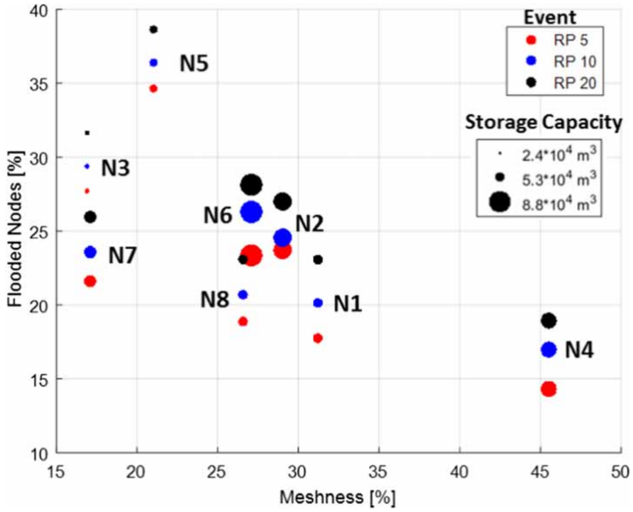

Figure 5 | Relationship between Meshness and node flooding for eight networks and three return periods (RP). Symbol size is directly proportional to the sewer storage capacity of each system.

nodes than N3. This can be attributed to the fact that the sewer storage volume of N7 is around 2.5 times larger than that of N3. The high percentage of flooded nodes for N5 may be equally related to a lower storage capacity and scarce number of alternative flow paths, and furthermore be a consequence of the equalization of drainage areas among the systems. In fact, this network was designed for a smaller and less impervious drainage area than the ones used for simulations. Therefore, the runoff values generated from the storm events exceed greatly the original design capacity of the system, thus leading to a higher number of flooded nodes than expected.

In networks with higher Meshness, the role of sewer storage capacity in flood occurrence becomes less clear. Although N6 and N2 have larger storage volumes and Meshness values similar to N8 and N1 (between 26% and 32%), results indicate a higher percentage of flooded nodes in these systems. This suggests that the increase of alternative flow pathways contributes prominently to the reduction of node flooding rates. This analysis, however, needs to be extended to further study cases in order to consolidate understanding of the effects of increasing Meshness.

Influence of Meshness on flood volumes and durations of such events can be seen in Figure 6, which exemplarily shows the empirical cumulative distributions of all the volumes and durations from all the flooded nodes in each network. These results are obtained from the simulations using the 10-year return period rain event. The other two precipitation scenarios yield outcomes with similar patterns and are therefore not presented separately here. As Figure 6 illustrates, flood events in the network with a higher

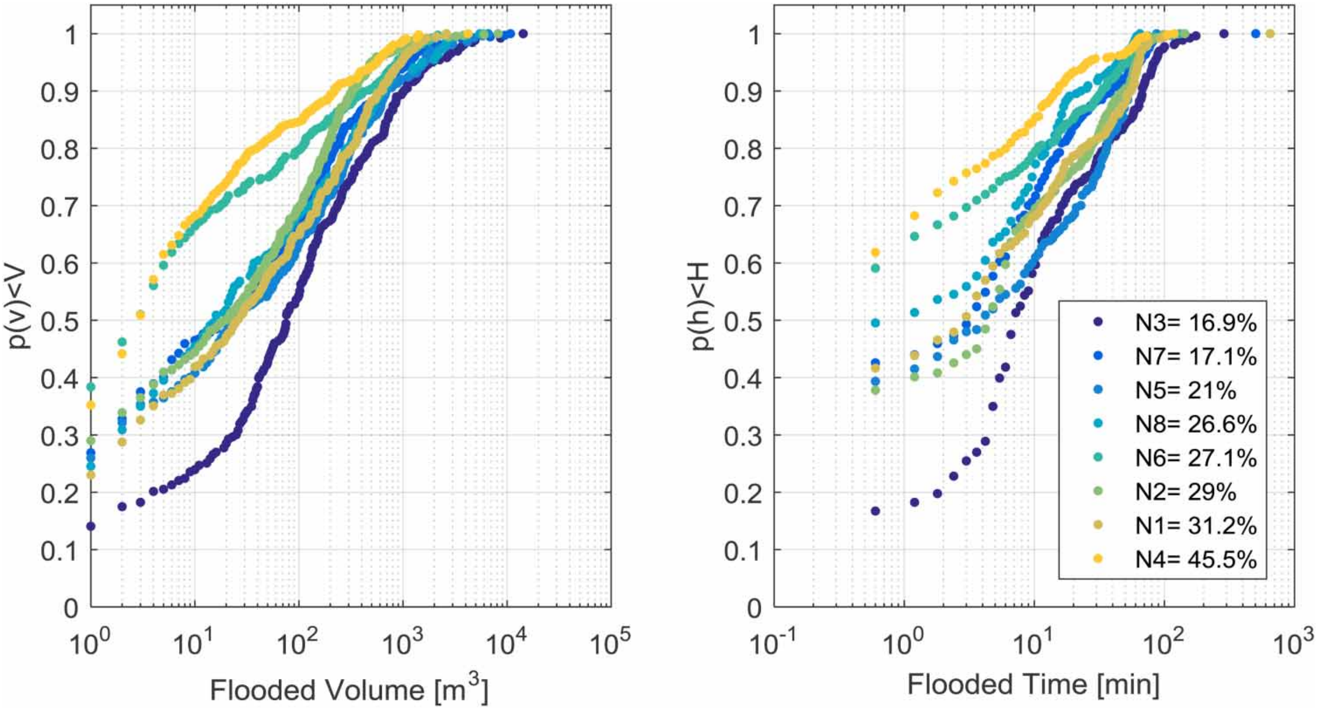

Figure 6 | Simulated cumulative distributions of flooding volumes (left) and durations (right) for all affected nodes in each of the eight Dresden subnetworks. Results are obtained for the 10-year return period scenario. Colored legend indicates the network and its Meshness in [%]. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wst.2020.070.

Meshness value (N4 = 45.5%), represented as yellow dots, are associated with smaller volumes (left panel of Figure 6) and shorter durations (right panel of Figure 6), than the events of N3 (represented as dark blue dots), the network with the lowest Meshness, i.e. 16.9%. In order to substantiate this, focus for example, on the 80th percentile values ($p(v) < V = 0.8$ in the figure) for both cumulative flood volumes and duration distributions of both systems. In the first case and as can be seen in the left panel of Figure 6, 80% of the flood volumes for N4 (the more meshed network) are equal to or smaller than 30 m^3 while for N3 (the more branched network) this value is one order of magnitude higher, at approximately 400 m^3. Such a difference is confirmed by the total amount of flooding volumes, 4,230 and 14,280 m^3 for N4 and N3, respectively. The distribution of flooding times, as depicted in the right panel of Figure 6, evolves similarly. In this case, the 80th percentile of the flooding events in N4 has a duration shorter than six minutes while for the branched system (N3), the equivalent 80% corresponds to a duration equal to or shorter than 30 minutes. Results indicate then that for a similar extreme precipitation scenario, flooding events in UDNs with a more meshed topology tend to have shorter durations and lower magnitudes than networks with a more branched layout. The other networks, with Meshness within the aforementioned range of N3 and N4, also remain intermediate in terms of flood volumes and duration. As previously discussed for node flooding, the order of flooding extent is not entirely consistent with the Meshness, hinting at other structural properties for failure magnitude.

Figure 7 illustrates the relation between flooded node and volume reliability indexes (R_n left and R_v right panel, respectively) as a function of Meshness. For the first aspect, reliability was higher than 75% for all layouts analyzed, thus indicating that node flooding rarely occurs for all the analyzed topologies. Nevertheless and in agreement with the previous evaluation aspects, meshed systems prevent flooded nodes slightly more reliably than branched systems. This implies that the probability of a node to cause flooding decreases as a function of increasing network Meshness.

Flooding volumes exhibit a similar relation to Meshness. In branched systems, considerably more flood volume occurs than in meshed systems. Hence, reliability indexes differ substantially with 39% for the lowest Meshness and 92% for the highest Meshness. The influence of network Meshness on reliability against flood volumes is higher than for reliability against flooded node number. The lower reliability of some networks against flooding may result from the selected storm return periods. While five- to 20-year storms were

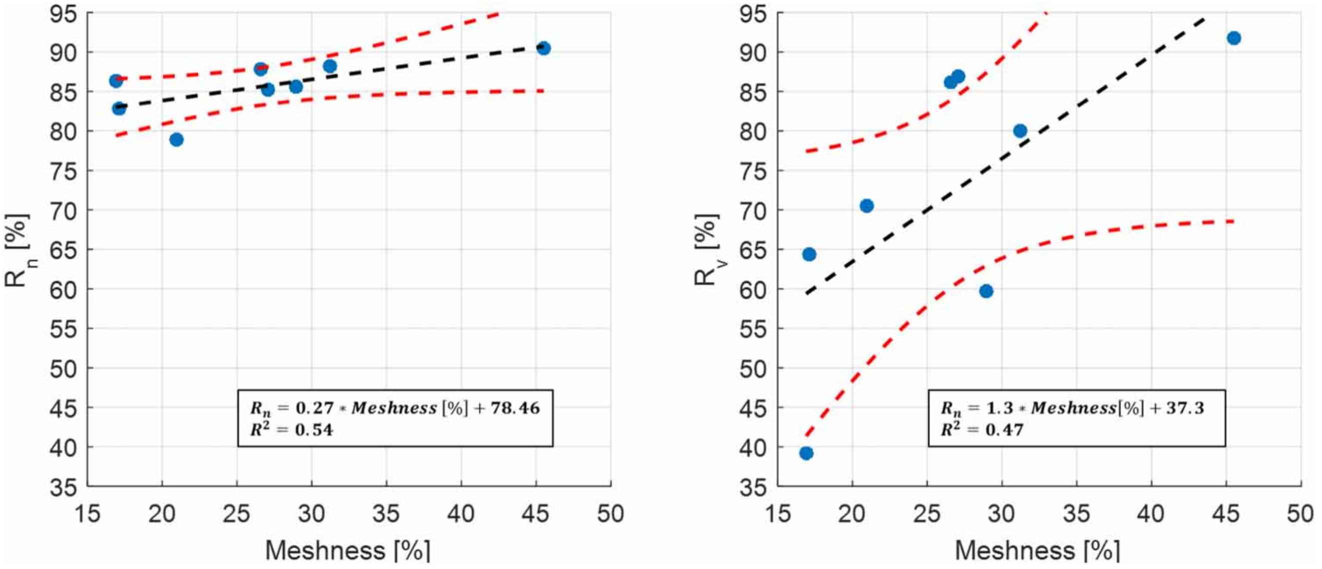

Figure 7 | Reliability indexes of flooded nodes R_n (left) and flooding volumes R_v (right) as functions of Meshness, including fitted lines, their 95% prediction intervals (black and red lines respectively) and fitted equations. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wst.2020.070.

simulated, German design guidelines require a surface flooding return period of less than 1 to 10 years, depending on the damage potential at the affected urban area (DWA-A118 2006).

The relation between network structure and its reliability is analyzed with linear regressions between the Meshness values and reliability indexes of the analyzed study cases. Results, including 95% prediction intervals, can be seen in Figure 7. The relations fit moderately, with coefficients of determination around 0.7, but both offsets and slopes are highly significant at *p*-values below 0.05. The comparison of the slopes of the fitted lines in both cases (depicted as black lines), suggests that Meshness plays a stronger role in reliability against flood volumes than in the occurrence of the flooding event itself, at least in the current study case. In fact, while node reliability (R_n) increases only 0.27% for every percent increase in Meshness, reliability against flooding volume (R_v) increases by 1.3%. The slopes and offsets of both relations are expected to be system-specific and dependent on the driving storm event selection. UDNs designed with lower flooding prevention requirements may exhibit generally lower flood reliability for the same range of Meshness. In contrast, using storm events of lower return periods or time series as input will likely increase flood reliability indicators. Isolating the effects of conditional, structural and topological influential factors is possible under the presented framework but requires a substantially larger number of study cases. Exemplarily, Bujang *et al.* (2017) determined a required minimum sample size of nine to 156 observations for multiple linear regression with two to ten influential factors and a resulting coefficient of determination between 0.1 and 0.7.

Conclusively, the topology of UDNs can play an important role in the occurrence and magnitude of functional failures, such as node flooding. As stated before, a potential reason for this relies on the presence of extra pipes for meshed networks, providing alternative flow paths and additional storage capacity, thus ensuring a better distribution of stormwater and activation of available storage capacity downstream of bottlenecks. Hence, they provide a continuous drainage of wastewater from all parts of the network. In this context, Meshness can be interpreted as a measure of redundancy in UDNs, i.e. a level of overlapping function that allows a system to adapt in order to preserve its main functions (Hassler & Kohler 2014).

Redundancy has been identified as one of the key characteristics of resilient systems (Cuppens *et al.* 2012; Butler *et al.* 2014; Francis & Bekera 2014). In the context of urban drainage systems, strategies for the enhancement of the network's redundancy have usually focused on increasing the storage capacities of the system, either by adding new storage tanks, temporary storage areas or increasing the capacity of critical pipes (see e.g. Butler & Davies 2011). Promoting Meshness in the system could then be considered as an alternative strategy for improving the UDN's storage capacity and henceforth increasing its redundancy. It is worth noticing, however, that the implementation of additional pipes (i.e. enhancement of the Meshness level of the network) may result in a substantial increase in the installation costs of the system. Further studies on determination of an adequate Meshness degree in a UDN should thus analyze the cost–benefit tradeoff. Furthermore, increasing the Meshness level may not improve system performance of the entire network. It rather seems to be a promising strategy for critical locations and predominantly branched existing layouts. Moreover, surface layout and property situation need to facilitate the meshed sewer design.

It is hypothesized that the additional storage provided by increased Meshness can also be used to distribute stormwater volumes in the network more evenly. In addition to improved flooding reliability, this may reduce high flow rates upstream of the overflow structures and hence reduce the number and the extent of combined sewer overflow events. This research focused on a comparative study of networks with varying Meshness. This parameter is directly related to the sewer storage capacity as can be seen in Supplementary Data 2. Additional research could analyze the role of multiple flow paths, associated with higher Meshness, on flooding occurrence. This could be achieved by designing and evaluating networks with a similar total storage capacity but different layouts, i.e. different Meshness degrees. Another extension of the present research could focus on the variation of Meshness in single networks and its implication for reliability against flooding.

CONCLUSIONS

The present study focused on the characterization of the most common topologies of UDNs and on their influence regarding the occurrence of node flooding. Their topology is characterized by the number of connections between neighboring sewer sections. A novel method quantified the similarity of a UDN's layout to a branched or a meshed system. A Meshness coefficient is calculated based on concepts and methods derived from graph theory. Meshness values close to 0% indicate networks with a branched layout, while 100% Meshness corresponds to topologies similar to a grid-like pattern. Results from a data set of 118 independent sewer subnetworks of 32 cities indicated that most UDNs have a branched or predominantly branched topology. Furthermore, hydrologic–hydrodynamic models for eight of the studied UDNs simulated their behavior during intense rain events that lead to functional failures. Results indicated that in UDNs with a higher Meshness, occurrence of node flooding events was less likely. Furthermore, they had smaller magnitudes and shorter durations than in more branched networks, thus making meshed UDNs more reliable.

Further research should consolidate understanding of the relationship between Meshness and node flooding. On the one hand, analyses should be extended to cover a wider range of Meshness. Results from this study suggested that the reduction of node flooding frequencies in networks with higher Meshness is associated with an increase of additional storage and number of alternative flow paths. Nevertheless, these factors do not play an equal role in all topologies. Storage had an influence on networks with a more branched structure (Meshness lower than 20%) but its effects were unclear in networks with higher Meshness, i.e. higher than 25%. Reductions of node flooding frequencies were then associated with the increase of alternative flow pathways. Nevertheless, these reductions might be influenced by other conditional, structural and topological factors. A larger number of study cases covering a wider variety of Meshness is needed to better understand the influence of increasing Meshness and other potential factors that may affect the occurrence of flood events. In particular, networks with low Meshness (less than 5%) need to be analyzed since they correspond to the most common UDN topology (approximately 70% prevalence). On the other hand, the combined effects of network structures such as storage tanks and CSOs need to be considered.

The Meshness of a UDN can be interpreted as a measure of redundancy. Such a parameter could support the development of new design and mitigation strategies, in order to improve UDNs' reliability. In this context, the results obtained in this study emphasize the importance of the role that structure and topology play in the function of sewer systems. It is expected that the outcomes of the present study could serve as a basis for the development of new operational and management strategies for the reduction of functional failures based on structural analysis.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Baños, R., Reca, J., Martínez, J., Gil, C. & Márquez, A. 2011 Resilience indexes for water distribution network design: a performance analysis under demand uncertainty. *Water Resources Management* **25** (10), 2351–2366.

Buhl, J., Guatrais, J., Reeves, N., Solé, R. V., Valverde, S., Kuntz, P. & Theraulaz, G. 2006 Topological patterns in street networks of self-organized urban settlements. *European Physical Journal B* **49**, 513–522.

Bujang, M. A., Sa'at, N. & Sidik, T. 2017 Determination of minimum sample size requirement for multiple linear regression and analysis of covariance based on experimental and non-experimental studies. *Epidemiology Biostatistics and Public Health* **14** (3), e12117.

Butler, D. & Davies, J. W. 2011 *Urban Drainage*, 3rd edn (Spon Press). Taylor and Francis Group, London, UK and New York, USA.

Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K. & Astaraie-Imani, M. 2014 A new approach to urban water management: Safe and SuRe. *Procedia Engineering* **89**, 347–354.

Butler, D., Ward, S., Sweetapple, C., Astraie-Imani, M., Diao, K., Farmani, R. & Fu, G. 2016 Reliable, resilient and sustainable water management: the Safe & SuRe approach. *Global Challenges* **1**, 63–77.

Casal-Campos, A., Sadr, S. M., Fu, G. & Butler, D. 2018 Reliable, resilient and sustainable urban drainage systems: an analysis of robustness under deep uncertainty. *Environmental Science & Technology* **52**, 9008–9021.

Creaco, E., Franchini, M. & Todini, E. 2014 The combined use of resilience and loop diameter uniformity as a good indirect measure of network reliability. *Urban Water Journal* **13** (2), 167–181.

Cuppens, A., Smets, I. & Wyseure, G. 2012 Definition of realistic disturbances as a crucial step during the assessment of resilience of natural wastewater treatment systems. *Water Science and Technology* **65**, 1506–1513.

DWA-A118 2006 *Arbeitsblatt DWA-A 118 Hydraulische Bemessung und Nachweis von Entwässerungssystemen.* DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V, Hennef, Deutschland.

Elsner, J. B., Jagger, T. H. & Fogarty, E. A. 2009 Visibility network of United States hurricanes. *Geophysical Research Letters* **36**, L16702.

Francis, R. & Bekera, B. 2014 A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety* **121**, 90–103.

Haghighi, A. & Bakhshipour, A. E. 2016 Reliability-based layout design of sewage collection systems in flat areas. *Urban Water Journal* **13** (8), 790–802.

Hassler, U. & Kohler, N. 2014 Resilience in the built environment. *Building Research & Information* **42**, 119–129.

Jayaram, N. & Srinivasan, K. 2008 Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing. *Water Resources Research* **44** (1), W01417.

Junghänel, T., Ertel, H. & Deutschländer, T. 2017 *Bericht zur Revision der koordinierten Starkregen regionalisierung und -auswertung des Deutschen Wetterdienstes in der Version 2010.* KOSTRA-DWD-2010R, Deutscher Wetterdienst Abteilung Hydrometeorologie, Offenbach am Main, Germany.

Kaeseberg, T., Kaeseberg, M., Zhang, J., Jawitz, J. W., Krebs, P. & Rao, P. S. C. 2018 The nexus of inhabitants and impervious surfaces at city scale – wastewater and stormwater travel time distributions and an approach to calibrate diurnal variations. *Urban Water Journal* **15** (6), 576–583.

Kruskal, J. B. 1956 On the shortest spanning subtree of a graph and the traveling salesman problem. *Proceedings of the American Mathematical Society* **7**, 48–50.

Lee, E. H. & Kim, J. H. 2019 Development of a reliability index considering flood damage for urban drainage systems. *KSCE Journal of Civil Engineering* **23** (4), 1872–1880.

Lee, J., Chung, G., Park, H. & Park, I. 2018 Evaluation of the structure of urban stormwater pipe network using drainage density. *Water* **10** (10), 1444.

Mahmoodian, M. & Alani, A. M. 2013 Multi-failure mode assessment of buried concrete pipes subjected to time-dependent deterioration, using system reliability analysis. *Journal of Failure Analysis and Prevention* **13** (5), 634–642.

Martinez, J. B. 2010 Cost and reliability comparison between branched and looped water supply networks. *Journal of Hydroinformatics* **12** (2), 150–160.

Prasad, T. D. & Park, N. S. 2004 Multiobjective genetic algorithms for design of water distribution networks. *Water Resources Planning and Management* **130** (1), 73–82.

Reca, J., Martínez, J., Baños, R. & Gil, C. 2008 Optimal design of gravity-fed looped water distribution networks considering the resilience index. *Water Resources Planning and Management* **134** (3), 234–238.

Rodríguez, J. P., McIntyre, N., Díaz-Granados, M. & Maksimović, Č. 2012 A database and model to support proactive management of sediment-related sewer blockages. *Water Research* **46** (15), 4571–4586.

Rossman, L. A. 2015 *Storm Water Management Model, User's Manual, Version 5.1.* EPA/600/R-14/413b, USEPA, Cincinnati, OH, USA.

Shannon, P., Markiel, A., Ozier, O., Baliga, N. S., Wang, J. T., Ramage, D., Amin, N., Shwikowski, B. & Ideker, T. 2003 Cytoscape: a software environment for integrated models of biomolecular interaction networks. *Genome Research* **13** (11), 2498–2504.

Thorndahl, S. & Willems, P. 2008 Probabilistic modelling of overflow, surcharge and flooding in urban drainage using the first-order reliability method and parameterization of local rain series. *Water Research* **42** (1), 455–466.

Tran, H. D. 2016 Markov-based reliability assessment for hydraulic design of concrete stormwater pipes. *Journal of Hydraulic Engineering* **142** (7), 06016005.

Wang, S., Fu, J. & Wang, H. 2019 Unified and rapid assessment of climate resilience of urban drainage system by means of resilience profile graphs for synthetic and real (persistent) rains. *Water Research* **162**, 11–21.

Yazdani, A. & Jeffrey, P. 2012 Applying network theory to quantify the redundancy and structural robustness of water distribution systems. *Journal of Water Resources Planning and Management* **138** (2), 153–161.

Yazdani, A., Appiah Otoo, R. & Jeffrey, P. 2011 Resilience enhancing expansion strategies for water distribution systems: a network theory approach. *Environmental Modelling & Software* **26**, 1574–1582.

Zhang, C., Wang, Y., Li, Y. & Ding, W. 2017 Vulnerability analysis of urban drainage systems: tree vs loop networks. *Sustainability* **9** (3), 397.

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